THE JOURNAL
OF THE
ROYAL AERONAUTICAL SOCIETY

(FOUNDED 1897 in succession to the ANNUAL REPORTS)

Edited for the Council by J. LAURENCE PRITCHARD, Fellow

No. 185. MAY, 1926. Vol. XXX.

NOTICES

President

At a Council Meeting on April 13th, Air Vice-Marshal Sir W. Sefton Brancker, K.C.B., A.F.C., Fellow, was unanimously elected President of the Society.

Elections

The following Members were elected at a Council Meeting held on April 13th :—

Associate Fellows.—Mr. A. S. Halliday and Flight-Lieutenant E. J. D Townesend, R.A.F.

Associates.—Mr. J. E. Atkins, Mr. H. V. Bullbrook, Mr. T. Hampson, Flight-Lieutenant R. P. Preston, Mr. F. A. I. Muntz, Mr. G. C. D. Russell, and Mr. D. G. Snook.

Members.—Colonel C. de F. Chandler, Sir Robert Waley Cohen, and the Master of Elibank.

Busk Studentship in Aeronautics

A vacancy has arisen for the Busk Studentship in Aeronautics for the year 1926-27. This Studentship was established in memory of Edward Teshmaker Busk, who in 1914 lost his life whilst flying an experimental aeroplane.

The Trustees hope to make an appointment towards the beginning of July next.

The Studentship is of the value of about £150, tenable for one year from October 1st ; but a student may be re-appointed on the same terms for a second year. It is open to any man or woman being a British subject and of British descent who has not attained the age of 25 years on October 1st next.

The object of the Studentship is to enable the holder to engage in research, or preparation for research in aeronautics.

Forms of Application for the Studentship can be obtained from

PROFESSOR B. MELVILL JONES,
Engineering Laboratory,
Cambridge,

and must be filled up and returned to him not later than May 12th next.

Applicants should state the date of their birth, their parentage and the parentage of their parents, together with their previous training and qualifications for research in aeronautics and the subject of their proposed investigations.

They should also give the names of two persons to whom reference may be made by the Trustees, and should state their readiness, if elected, to comply with the conditions of the Studentship.

Any inquiries relating to the Studentship should also be addressed to Prof. Jones.

Visits

The attention of Members in all grades is drawn to the visits arranged by the Students' Section. Any Member who wishes to join the Students' Party should send a postcard to the Secretary saying that he will attend the visit. In the case of the visit to Farnborough, Members should state their nationality.

The Students' Visit to the de Havilland Aircraft Company's Works was greatly enjoyed. Each visitor was given a flight in a D.H. Moth.

Committees and Representatives on Other Bodies

The following Members of Committees and Representatives on other bodies were re-appointed at a Meeting of Council held on April 13th :—

Candidates' Committee.
Professor L. Bairstow, Major T. M. Barlow, Major B. C. Carter, Professor B. Melvill Jones, Major Mayo, Professor A. J. Sutton Pippard, Major G. H. Scott, Mr. T. O. M. Sopwith, and Mr. C. W. Tinson.

Finance Committee.
Mr. G. Brewer, Mr. C. R. Fairey, Mr. A. E. Turner, and Mr. F. P. Walsh.

Data Sheets Committee.
Captain Gillman, Major Low, Mr. Manning, and Major Mayo.

Informal Discussions Committee.
Wing Commander T. R. Cave-Browne-Cave, Mr. Manning, and Major Mayo.

Joint Standing Committee with the Society of British Aircraft Constructors and the Royal Aero Club.
Professor L. Bairstow, Wing Commander T. R. Cave-Browne-Cave and Mr. W. O. Manning.

British Engineering Standards Association Aircraft Committee.
Major R. H. Mayo and Colonel the Master of Sempill.

Central Library for Students.
Mr. J. E. Hodgson (Hon. Librarian).

Carnegie Trust

The Twelfth Annual Report of the Carnegie United Kingdom Trust, recently received, contains a mass of well-digested information on the work of the trust.

The Society is more particularly concerned with the work of the Trust in connection with grants to libraries. It was the generous grant of £500 to the Royal Aeronautical Society which enabled the Society to make its library one of the finest in the world.

Donations

Miss Gertrude Bacon has presented to the Society several books which were in the library collected by her late father, Mr. J. M. Bacon, the well-known balloonist and author of *The Dominion of the Air* and *By Land and Sky*.

Library Fund

The Council desire to express their appreciation of the generous way in which members who have had their subscriptions reduced have allowed the balance to be added to the Library Fund. In addition to the gifts recorded in the March and April journals are the following :—Air Vice-Marshal Sir Edward L. Ellington, 14s. ; Lieutenant-Colonel M. O'Gorman, £1 1s. ; and Flight-Lieutenant O. H. D. Vickers, £2 2s.

The Institute of Physics

Mr. H E. Wimperis, O.B.E., Fellow, will deliver a lecture on "The

Relationship of Physics to Aeronautical Research," on Tuesday, May 11th, at 5.30 p.m. in the Physics Theatre of the Royal College of Science, South Kensington. Members of the Royal Aeronautical Society are invited to attend.

List of Members

A new List of Members will be published shortly. Will members please inform the Secretary of any alterations to their style and title.

Wilbur Wright Memorial Lecture

The title of the lecture which Mr. F. W. Lanchester will deliver on May 27th, is "Sustentation in Flight." Before reading the paper, Mr. Lanchester will be presented with the Society's Gold Medal.

Students' Section Programme

Saturday, May 8th.—Visit to Fairey Aviation Works. Meet at booking office, Paddington Station at 9 a.m. sharp.

Wednesday, May 19th.—Visit to the Royal Aircraft Establishment. Will all those wishing to go please send their name and nationality to the Secretary at once? Meet at Main Line Booking Office, Waterloo Station, at 10.0 a.m. sharp. The visit will be an all day one. Arrangements are kindly being made for lunch at the R.A.E. Canteen. The number visiting is limited to 30.

The Month's Arrangements

Saturday, May 8th.—Visit to Fairey Aviation Works.

Tuesday, May 18th.—Council Meeting, 5.30 p.m.

Wednesday, May 19th.—Visit to Royal Aircraft Establishment, Farnborough.

Thursday, May 27th, 6.30 p.m.—Wilbur Wright Memorial Lecture. In the Library. "Sustentation in Flight," by Mr. F. W. Lanchester, Honorary Fellow.

Coventry Branch

Mr. Alan Cobham's lecture, arranged by the Coventry Branch, took place on 27th April, 1926. An enthusiastic audience of nearly 2,000 people gave him a memorable reception. The Mayor of Coventry (Alderman F. Snape) presided. Mr. Cobham showed a number of slides, and the Honorary Secretary of the Coventry Branch (Mr. F. Meadows) sums up the effect of the lecture by saying that "had we a few more Cobhams I could enrol the whole of Coventry as members of our Branch."

The next lecture before the Coventry Branch will be given by Mr. Handley Page, C.B.E., Fellow, at 7.30 p.m., on May 18th, 1926, in the Armstrong-Siddeley Social Club. The title of the lecture is "The Stability and Control of Aircraft."

Glasgow Branch

Flight Lieutenant B. C. Cross lectured on Monday, April 19th, to the 400 Cadets of the Public Schools of Glasgow, on "The Flying Boat in Peace and War." He also lectured in the evening to the Beardmore Aviation Engineering Society, Dalmuir, on "Some Practical Aspects of Flying Boat Development."

Lantern Slides

The Council desire to record their grateful thanks to the following firms who have presented sets of slides of their latest machines to the Society's Loan Collection for the use of members:—The Gloucestershire Aircraft Co., Ltd.; Rolls-Royce, Limited; and Vickers, Limited.

J. LAURENCE PRITCHARD,

Hon. Secretary.

PROCEEDINGS

First Meeting, Second Half, 61st Session

A meeting of the Royal Aeronautical Society was held in the Library at 7, Albemarle Street, on Thursday, January 7th, 1926, at 6.30 p.m., when Professor A. J. Sutton Pippard read a paper on "The Experimental Stress Analysis of Frameworks, with Special Reference to the Problems of Airship Design." Sir Sefton Brancker, Chairman of the Society, presided.

THE EXPERIMENTAL STRESS ANALYSIS OF FRAMEWORKS WITH SPECIAL REFERENCE TO THE PROBLEMS OF AIRSHIP DESIGN

PROF. A. J. SUTTON PIPPARD, M.B.E., D.SC., F.R.AE.S.

Following the accident to H.M. Airship R.38 at the end of August, 1921, the Accidents Investigation Sub-Committee of the Aeronautical Research Committee was requested by the Director-General of Supply and Research, Air Ministry, to carry out an investigation of all technical details which contributed to the accident. This was done and the Report of the Committee was published early in the following year.

The Summary of their findings was arranged under sixteen heads, one of which was as follows: "The existing methods of calculation at present in use for determining the scantlings of structural members of an airship are insufficiently accurate for the purpose and more exact methods should be developed."

The Air Ministry, in view of this conclusion, approved the formation of a Panel of the Aeronautical Research Committee having as terms of reference the consideration of the validity of the methods in use for calculating the strength of rigid airships, and the indication of other methods which would enable a closer basis of design to be obtained. This Panel, which became known as the "Airship Stressing Panel," worked under the chairmanship of Mr. R. V. Southwell for a period of about eight months, terminating its activities in August, 1922. The results of its work were published as a Report of the Aeronautical Research Committee (R. and M. 800) and this report contained a considerable amount of new theoretical work dealing with the stress distribution in elementary frameworks conforming in essentials to the hull of a rigid airship. These results were only obtained by the introduction into the analysis of various simplifying assumptions and the validity of these required checking. To quote the Airship Stressing Panel's report: "By means of a model in which the assumptions of the theory can be more or less exactly reproduced, a direct check may be imposed. The Panel accordingly desires to recommend that experiments be initiated now on models representative of the structure of a rigid airship as a check on the theoretical results of this report. In its view, the first requirement is to establish reliable formulæ for general use, and all experimental work, whether on the model or full-scale, should be directed towards this end."

At the end of the following year—1923—the present writer being in a position to undertake experimental work, suggested to the Aeronautical Research Committee that he should carry out a research into the properties of redundantly braced frameworks, partially with a view to throwing some light on the problem of the rigid airship hull. This course was agreed to, and the experimental work

was begun almost immediately and has proceeded continuously up to the present date at Cardiff University College. It is the results of these experiments that will be brought before the Society this evening. Before proceeding to a discussion of the experimental methods and results, it is essential to consider for a short space the work of the Airship Stressing Panel and its line of attack.

Work of the Airship Stressing Panel

The rigid airship hull, as it was known at the time when the Panel began work, consisted of a braced tubular framework exhibiting a very high degree of redundancy. Theoretically, any redundant framework is capable of exact stress analysis, making the usual assumptions as to elasticity of the members, etc., but since, at a moderate estimate, the determination of stresses in R.38 would have entailed the solution of a thousand or so simultaneous equations, the Panel had no hesitation in deciding that an exact solution was impossible of achievement. The problem then became to find methods which, while admittedly approximate, were sufficiently accurate for design purposes and at the same time as simple in use as possible. After some discussion of the possibilities of the situation it was decided that the only real chance lay in devising formulæ analogous to those used by every engineer in designing a girder.

The method in this everyday job is to determine the bending moment and shear at each section of the girder, and then to apply formulæ of a very simple type to find the necessary cross sections. This does not give a mathematically exact result, but that it is sufficiently correct for all practical purposes is proved by experience and direct experimental evidence. It should be noticed in particular that when this method is used, no attention is paid to the manner in which the external loads are applied—all that is required is a knowledge of the resultant actions at the section considered: further, the shape of sections other than the one considered is not introduced into the calculations.

If corresponding formulæ could be found for the case of a tubular framework, it was evident that the work of design could be reduced to a comparatively simple routine. Fortunately for the success of the Panel's work, Mr. Southwell had already begun a series of investigations along these lines, inspired by the problem of the torsional stresses in an aeroplane fuselage, and this formed a good foundation for the work. A discussion of the details of the work forms no part of the object of this paper, but an outline is necessary.

Solutions were found for the stresses in a braced tube of uniform cross section under the action of bending moments, torsions and shearing forces upon the assumption that the cross sections were free to warp out of their planes. In order to obtain these solutions it was necessary to postulate that the straining systems were applied in a particular manner. If the same resultant actions were applied in a different way the stresses would not be the same in the immediate vicinity of the applied forces, but reliance was placed in the hope that St. Venant's principle was applicable to a redundant frame. If this were so, the stresses at a distance from the applied forces would be practically independent of the manner of their application. A further simplification of the problem was possible if it could be assumed that the transverse frames did not warp out of their own planes under load, *i.e.*, if plane sections before straining remained plane after straining. There was some justification for the hope that this might be the case in a rigid airship hull, since some section amidships must be plane and the ends are constrained by the pyramidal bow structure and the structure supporting the control surfaces respectively. A further contribution to the subject was made by the exact solution of the case of a pin-jointed hexagonal framework of tubular form subjected to a uniform shear, when one end was constrained to remain plane. This solution was a general one and applicable to a tube of any length, and was due to Miss L. Chitty, who was working with the Panel.

The work upon the assumption that plane sections remained plane was extended to the case of a uniformly tapered tube, and so formulæ were obtained which it was hoped would cover both the approximately parallel mid section of a ship and the tapering ends. It will be realised, however, that the assumptions necessary to obtain the generalised formulæ required verification, and hence the recommendation of the Panel previously quoted and the work to be described.

The detailed analysis by Miss Chitty, referred to above, showed that the structure she examined was probably the most complicated which was amenable to exact mathematical treatment, and for this reason it was felt wise to take the same framework as a starting point for the experimental work.

The hypothetical framework consisted of six longitudinal members, and was divided into a number of equal bays by transverse frames in the form of regular hexagons; the panels thus formed by the transverse strut members and the longitudinals were braced across both diagonals. The end transverse to which the external load was applied was assumed to be rigid in its own plane, but free to warp out of that plane; the remaining transverse frames, which were unbraced in their own planes, were assumed to be formed of rigid members. The structure was assumed to be pin-jointed throughout, and all members were capable of withstanding either tensile or compressive forces. The longitudinal members were of equal size with the exception of the bottom or keel member, which the analysis permitted to be made of any desired cross sectional area.

By making the experimental framework correspond as nearly as practicable with the hypothetical structure described, it was possible to use the mathematical analysis as a check upon the accuracy of stress measurement. This was essential since the method of experimentation had to be applied to cases which were not amenable to exact solution.

This particular structure had the additional advantage that it could be used to investigate the validity and scope of some of the general formulæ previously referred to, which was one of the objects of the experiments.

Description of Structure

The leading dimensions of the experimental structure, and some details of its construction are shown in Fig. 1. The framework was three bays in length,

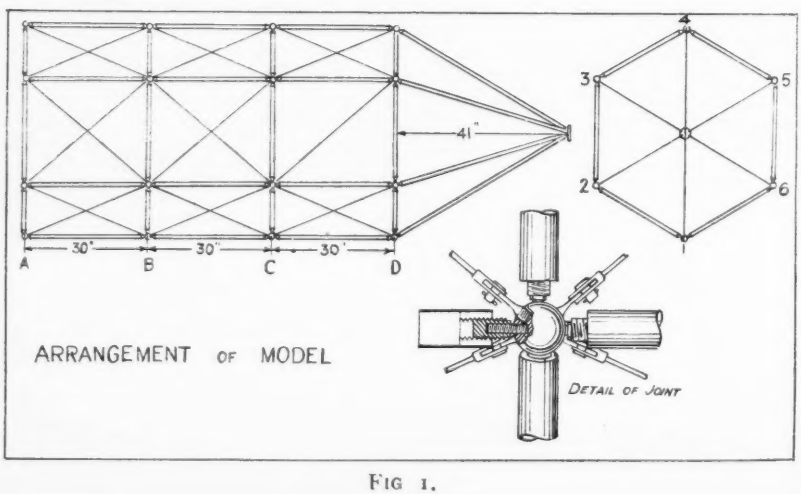

FIG 1.

each bay being 30in. long; the side of the hexagon was 25in. Since the theoretical analysis had been based on the assumption that the structure was pin-jointed throughout, an attempt was made to design a suitable joint of this type. The difficulties in this will be apparent, and although several designs were made it was found that even in the best of them the friction on the bearing surfaces would have been considerable, and would in fact have introduced a fixing factor of an incalculable amount. The attempt to obtain true pin or ball ends was therefore abandoned, and a suggestion made by Mr. R. V. Southwell was examined: this suggestion was that the members of the structure should be attached to the joints by short dowels or pins, which would be of sufficient cross sectional area to transmit the direct loads in the members, but so short that no tendency to buckle would occur. The necessary strength was given by dowels of small diameter and flexural rigidity; consequently the amount of bending which could be transmitted by them was small, and moreover could be calculated if necessary and allowed for as a correcting factor.

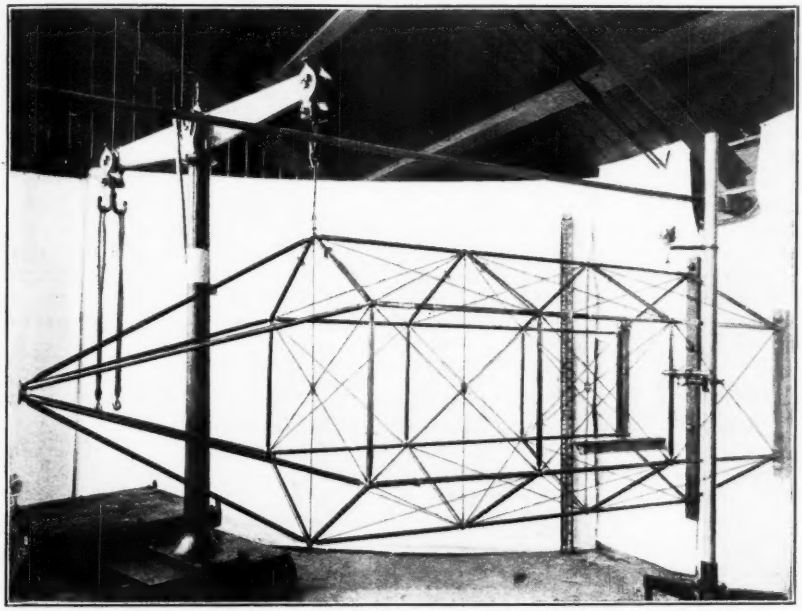

FIG. 2.

As a test of this method, two experimental struts 24in. long were carefully turned from mild steel bar to a uniform diameter of 0.75 inches. One was tested with the ends bearing on hard steel balls of 10mm. diameter, while the other was attached by steel dowels of 0.25 inch diameter to carefully faced end plates of large bearing area. The first, with its almost perfect ball-ends, crippled suddenly under an axial load of 7,900 pounds; the second, which reproduced the dowel attachment under consideration, failed at a load of 7,045 pounds. Careful tests gave the modulus of elasticity of the steel used in the struts as 30.6×10^6 pounds per square inch, from which the Euler critical load for the first strut was calculated to be 7,905 pounds.

It will be seen that the ball-ended strut reached practically the theoretical value of the crippling load, while that with dowel attachments gave rather less.

The figures provided evidence that the dowels might be relied upon to serve as a satisfactory means of attachment without introducing any serious fixing effect. The transverse and longitudinal members of the structure were made of steel tube ⅝in. outside diameter and 22g. thick to B.E.S.A. Specification T. 10. All cross bracing members were 4 B.A. swaged rods to B.E.S.A. Specification W. 8, ability to resist compression being obtained by initially tensioning these wires to such an extent that they remained operative under the maximum loads imposed. Steel liners ¾in. in length were soldered into the ends of each tube and were tapped to take plugs of ½in. diameter, the threads being left-handed at one end of the tube and right-handed at the other, this being necessary for the erection and trueing up of the structure. The dowels were 7/32in. diameter steel to B.E.S.A. Specification S. 2; one end was screwed home into the plug and the other into the joint of the structure, leaving 1/16in. between the faces of the joint and the plug. The joints were 1¼in. diameter Hoffmann steel balls partially softened and tapped to receive the dowels and the lugs for the attachment of the cross bracing wires. The wires were standard, the ends being respectively threaded left and right hand for trueing up, and were fastened to the wiring lugs in the usual way by steel pins. Provision was made for replacing the keel member by solid bars of ⅝in. diameter, since it was desired to carry out experiments upon the effect of varying the size of this member. A nosepiece of tubes in the form of a regular pyramidal structure was also provided: this is seen in the photograph of the structure (Fig. 2), and its purpose will be discussed at a later stage.

Three mild steel plates 1¼in. thick and 3in. wide were rag bolted in the same vertical plane to the main wall of the laboratory. The structure was attached to these by dowels of the same size as used in the joints. The structure was loaded at the free end by means of a beam weighing machine, one pan of which was replaced by a special hook fastened to the top joint of the structure, a turn-buckle being inserted between the beam and the joint so that the former could be brought to a horizontal position when the weights in the other pan were altered.

Measurement of Strains

Means for measuring the strains in all the members of the structure to a high degree of accuracy were essential, and for this purpose none of the standard types of extensometer were suitable, either on the score of weight or expense; in consequence, a special instrument had to be designed, and this was done in collaboration with the Cambridge Instrument Company, Limited.

Gauges made of thin aluminium, corrugated for the sake of stiffness, were attached to each member of the structure by a hardened steel knife edge and small setscrew; at the end of the gauge was a small circle of glass marked on the under side with two fine cross lines. The glass was held in contact with the member by small indiarubber bands. A fine line was scratched on the surface of the member to coincide as nearly as possible with the line on the glass. The distance between the scratches on the member and the glass was measured by a special microscope, and the alteration in this distance under different conditions of loading was the magnitude of the strain produced. The gauges were 15in. between the point of attachment to the member and the line on the glass. It was originally intended to measure the strain in compression members on a gauge length of 2in. in addition, in order to eliminate any bowing effect in these members, but it was found that this gauge length was too short to obtain satisfactory results. The scratches on the members of the structure were made by a Gillette safety razor blade; this was adopted after a number of other methods had proved unsatisfactory. The surface of the member was rubbed over a small area with emery paper: a special steel measuring bar 15in. long was then attached to the member in a similar manner to the gauges, the razor blade

being then lightly drawn across the polished surface, keeping it in contact with the end of the measuring bar. On removing the measuring bar from the member the mark made by the knife edge was sufficiently pronounced to register the gauge in the exact position occupied by the measuring bar; thus the scratch on the member and that on the glass were close together in the field of the microscope. The same method was used both for the tubular members and for the swaged wires and gave very good results. A second scratch crossing the first was made on the member in order that readings could always be taken to the same point; this was sometimes a part of the line and sometimes an accidental mark on the surface of the member close to the cross lines, which then served for location purposes.

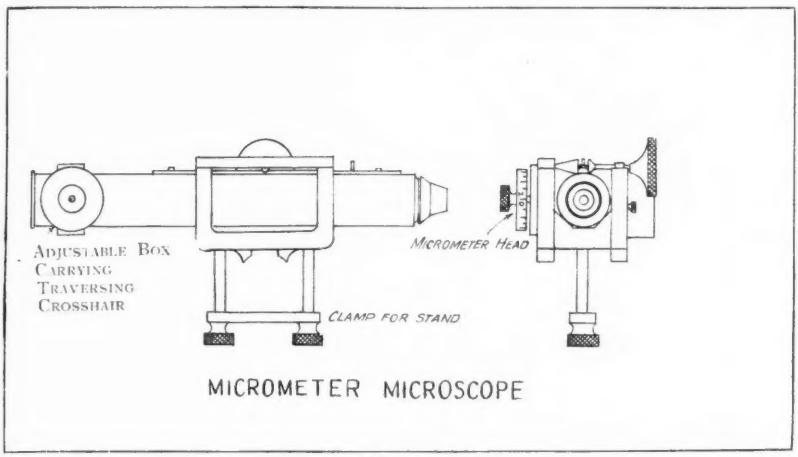

FIG. 3.

The microscope used is shown diagrammatically in Fig. 3. The optical arrangement is standard and needs no special description. The eyepiece is provided with a traversing cross hair operated by a micrometer head. This cross hair was first brought into coincidence with the line on the glass, and then traversed until it coincided with the scratch on the member. The readings of the micrometer head were noted in each case, and the difference gave the distance between the scratches.

The same procedure was followed after the structure had been loaded, and the difference between the readings before and after loading was the strain produced by the external load system. The movement of the traversing cross hair as measured by a standard grid was 1/17780 inch per division on the micrometer head, but actual calibration curves were used to reduce the micrometer head readings to loads in the member as will be described later.

The objective of the microscope was 2/3 inch, this being the smallest with which reasonable illumination could be obtained under the conditions in which the instrument was to be used. Illumination was obtained from a small 6-volt lamp carried on the end of the microscope; this ensured that the light was always in the same relative position to the scratches which were being viewed through the microscope, and thus errors due to variation of the angle from which the light fell were avoided. Since the microscope had to be used on all members of the structure in turn, it was carried on a steel tubular stand, 2in. diameter, mounted on a heavy tripod base. This stand was 7ft. high and the microscope could be attached to any part of it. A tubular extension arm at right angles to the vertical

post enabled the instrument to be placed in position for measurement upon the top and bottom members of the framework. The instrument on its stand, but without the extension arm, is shown on the right of Fig. 2, which also shows the gauges in position upon the structure ready for observation.

Preliminary Experiments and Calibration

Before applying a heavy load to the structure it was felt desirable to test the strength of the joints and dowels. A spare tube was held in the testing machine by joints of the pattern used in the structure, so that the whole load was transmitted through the solder holding the plugs to the tube. No sign of failure occurred until a load of 2,580 pounds was reached, when one plug slowly drew out. This showed a factor of safety of at least two on the maximum load it was intended to apply, and was considered satisfactory. Soldering, however, is a somewhat unreliable process, and several instances of failure occurred later during the conduct of the experiments. It was, however, a comparatively simple matter to resolder and replace the members which had failed. Failure was always due to some slight fault in soldering, and the method of construction has

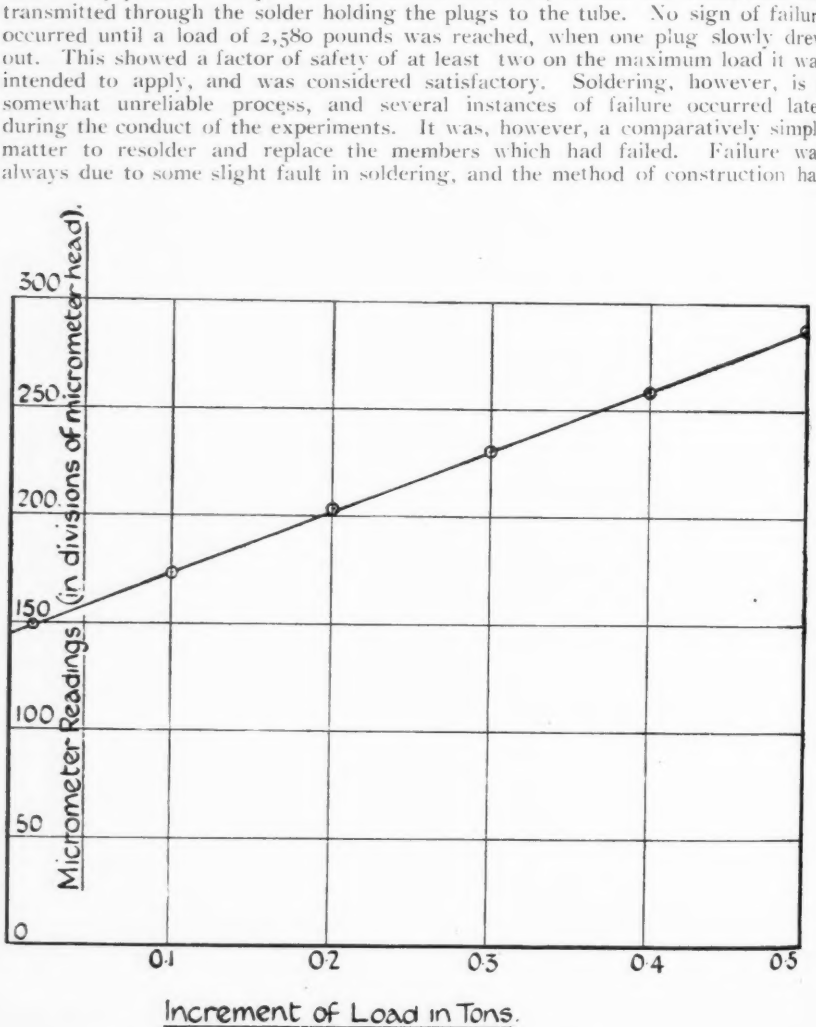

FIG. 4.
Calibration Curve for $\frac{1}{8}$" O.D. 22g. Tube. 15" Length.

on the whole proved quite satisfactory. Another test was made to determine the strength of the screwed dowels. The ends of the test piece were screwed into their appropriate plugs for a length of one diameter of the dowel (7/32in.). These plugs were then tested in tension. Failure occurred in the dowel at a load of 2,770 pounds, giving a large margin of safety upon any load which would be imposed. After the test, the dowel unscrewed perfectly from the plugs, and no injury of any kind could be detected to the thread either of the dowel, or of the plug.

The next step was to obtain calibration curves so that micrometer head readings of strains could be reduced directly to loads in the members. A typical tubular member was tested in the Buckton machine, one of the standard gauges being attached. Careful readings of the strain were made with the micrometer microscope for a number of loads. These micrometer head readings were plotted against the load to obtain the calibration curve for the tube shown in Fig. 4. A similar procedure was followed in the case of a 4 B.A. swaged rod, but since the cross sectional area is so small, direct loading was adopted. The calibration curve for this member is shown in Fig. 5. From these curves it will be seen

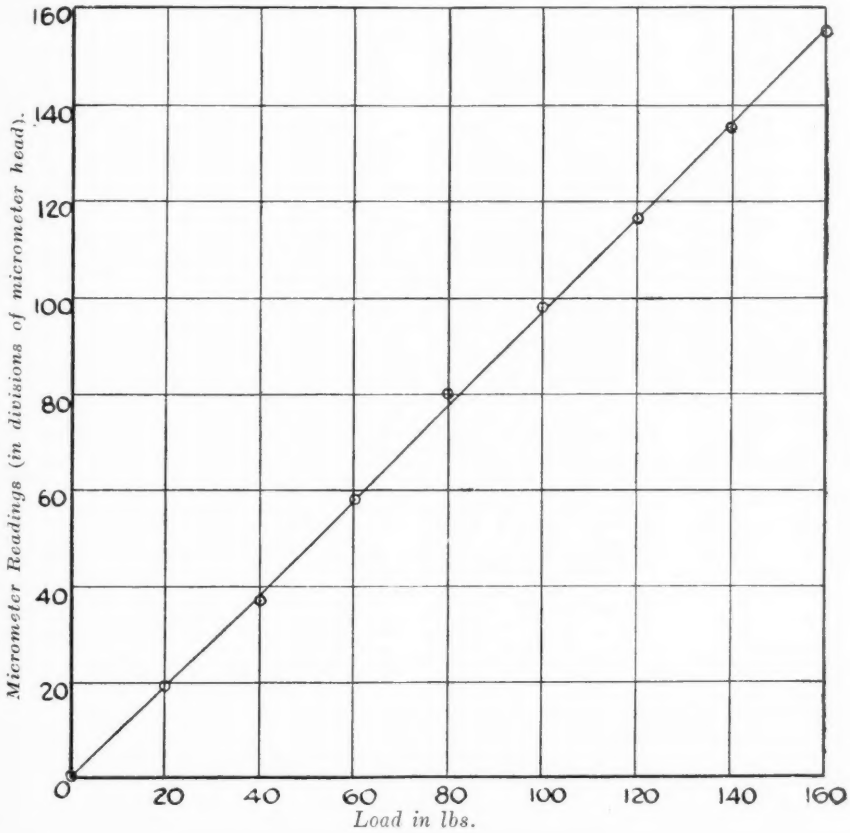

FIG. 5.
Calibration Curve for 4 B.A. Wire.
15″ Length.

that for the $\frac{5}{8}$in. × 22g. tube one division of the micrometer head, using a 15in. gauge length, is equivalent to a load of 7.84 pounds, and for a 4 B.A. swaged rod one division corresponds to a load of 1.02 pounds.

The Conduct of Experiments

The structure having been erected and trued up, the wires were tensioned so that they could operate as struts. The magnitude of these initial tensions was immaterial as long as they were sufficient to ensure effective strut action under the maximum load to be imposed. On loading the structure it was possible to judge whether the initial tensions were sufficiently high. Having adjusted the wires satisfactorily, an initial load was placed on the scale pan and the readings of the gauges taken. The desired increment of load was then applied and the readings again taken. The difference was then reduced to loads by the use of the calibration curves. It was originally intended to mount gauges on all members of the structure, and take readings on each in turn for one condition of loading; then to add load and once more take all readings. It was found, however, much more satisfactory to keep the microscope in position for one member, and to complete the two readings for it. This meant considerably more labour in loading and unloading than the other method, but was more accurate and reliable.

Having obtained a complete set of readings for the structure, certain checks could be applied as follows:—

(i) In the case of symmetrical loading the strain of the corresponding members on the two sides of the structure should be the same.

(ii) The vertical components of the forces in the members across any section should give the total vertical shear at that section. Thus, in the centre of each bay the total of the vertical components of the loads in the cross bracing wires should give the shear across that bay.

(iii) The forces in the members at each joint should give static balance.

After the first set of readings had been taken it was found that the errors as indicated by the out-of-balance forces at several joints were of a serious character, and repeat readings were made with no better result. Further investigation indicated that the probable source of error was due to some of the strut members bending slightly, so that the resultant strain due to direct compression and bending stress was being measured and not the direct compression alone. Since the members were circular in section this trouble was overcome by taking readings of strain at the opposite ends of any diameter: the average then gave the strain due to direct compression stress alone. When this was done results were very much better and within the limits of experimental accuracy, and the method was therefore always adopted in measuring strains of tube members in later experiments.

Experimental Errors

The main sources of possible error in obtaining experimental results are three in number, viz.:—

(i) Errors due to the limitation of the method of measurement.
(ii) Errors due to the variation in the sizes of the members of the structure.
(iii) Errors in reading the instrument.

(i) *Errors due to the limitation of the method.*—As already stated, one division of the micrometer head of the microscope corresponds to 1/17780in., and the magnification required entailed very delicate manipulation of the micrometer head if exact coincidence was to be obtained between the lines on the glass and on the specimen, and that on the traversing eye-piece. This,

however, was principally a matter of practice, and after some experience it was found to be a comparatively simple matter to obtain satisfactory results, and observations could be repeated to within about one division of the micrometer head, which is therefore assumed to be the limit of experimental accuracy. This will be seen on reference to the calibration curves to correspond to ± 8 pounds on the standard tube members and ± 1 pound on the wires. The small error on the wires makes the results obtained for these members particularly reliable and useful. Another difficulty arose from vibration of the laboratory, and it was found impossible to take readings if plant were running in certain parts of the buildings or if a heavy vehicle were passing outside. Such disturbances were, however, only occasional, and usually this trouble was not sufficiently serious to cause any prolonged interruption of the work.

(ii) *Errors due to the variation in the size of the members.*—All the material used in the structure was made to B.E.S.A. Specification for aircraft materials, in which great care is taken to ensure uniformity of quality and dimensions. Tolerances, however, are unavoidable, and in the case of the tubes the variation in thickness allowed by specification amounts to 7 per cent. Hence, due to this cause, the error in the readings of any tubular member may be $\pm 3\frac{1}{2}$ per cent., while the corresponding error in the wires may be the same.

(iii) *Errors in reading.*—Errors in reading the instrument were eliminated as far as possible by taking at least three measurements on each member. Even with this precaution, however, it was found that occasionally a wrong value for the strain was obtained, but this could always be detected by an application of the checks previously mentioned. Having obtained a complete set of readings for the structure, the out-of-balance force at each joint was expressed as components along three mutually perpendicular axes. If this out-of-balance force were serious, check readings were made in order to trace the error, but in the majority of cases the errors were within the limits of experimental accuracy. These errors were then distributed among the members of the structure at the joint concerned as far as was possible. This was of necessity a somewhat arbitrary matter, and the general method was to neglect the wires since the area of these was only one-tenth of that of the tube members. The out-of-balance force was then distributed between the tube members. It will be seen on reference to the experimental results that the corrections applied by this means to the measured loads were always very small and never exceeded the amount by which the reading might have been in error due to the causes enumerated above.

Experimental Results

In identifying the various members of the structure the following system has been adopted and is shown on Fig. 1. Each transverse frame is distinguished by a letter beginning at the fixed or wall end with A. Each joint in the transverse is numbered, beginning at the bottom with 1 and following round the frame in a clockwise direction viewed from the free end. The middle joint in a transverse frame is O. Thus each joint in the structure is denoted by a letter and a numerical suffix, *e.g.*, A_1, B_3, etc. A positive sign is used to denote a tensile load and a negative to denote a compressive load.

The experimental work upon this structure now fell into the following divisions :—

(*a*) A check upon the methods of measurement.
(*b*) The effect of varying the stiffness of the transverse frame bracing.
(*c*) The effect of a framed nosepiece in order to determine whether the assumption that plane sections remained plane was justified.
(*d*) A verification of a theorem relating to the torsion of a tubular framework.
(*e*) The effect of alterations in the distribution of external forces.

(*a*) *Check upon the methods of measurement.*—The object in this experiment was to reproduce the conditions assumed in the mathematical analysis as nearly as possible, so that a direct check upon the experimental methods could be obtained by comparison with the theoretical results. The main assumptions of the analysis were that the frame was pin-jointed throughout, and that the bulkhead to which the load was applied was rigid in its own plane but free to distort out of that plane.

In order to obtain this latter condition the radial bracing in the D bulkhead was formed of $\frac{5}{8}$in. steel rods pinned to a centre plate and to the nodes D_1, D_2, etc. All the longitudinal members were $\frac{3}{4}$in. O.D × 22g. steel tubes, and a load of 400lbs. was applied vertically upward at the joint D_4. The loads in all the wires were measured and these were found to be satisfactory when the checks previously mentioned were applied. The results of the measurements are given for one-half of the structure in Table I., together with the theoretical loads as found by calculation. The differences are very small, the greatest being 2.4 lbs., and in eleven out of the eighteen members the difference is less than the experimental limit of accuracy. This set of results indicates that the method of experimentation adopted was likely to prove satisfactory.

TABLE I.

Member.	Measured Load. lbs.	Calculated Load. lbs.	Difference. lbs.
A_1B_5	−72.8	−70.8	+2.0
A_5B_4	27.5	27.2	+0.3
A_5B_6	−106.5	−106.0	+0.5
A_6B_5	104.5	106.0	−1.5
A_6B_1	−27.1	−27.2	−0.1
A_1B_6	68.4	70.8	−2.4
B_4C_5	−63.5	−62.0	+1.5
B_5C_4	36.7	36.0	+0.7
B_5C_6	−105.0	−106.0	−1.0
B_6C_5	107.6	106.0	+1.6
B_6C_1	−35.7	−36.0	−0.3
B_1C_6	63.2	62.0	+1.2
C_4D_5	−52.0	−53.3	−1.3
C_5D_4	45.8	44.6	+0.8
C_5D_6	−105.5	−106.0	−0.5
C_6D_5	105.0	106.0	−1.0
C_6D_1	−43.8	−44.6	−0.8
C_1D_6	53.1	53.3	−0.2

A second check experiment, however, was made after the keel member had been replaced by a solid steel bar of $\frac{5}{8}$in. diameter, this being ten times the area of the other longitudinal members, which remained, as before $\frac{3}{4}$in. × 22g. In this experiment also the heavy bracing members in the D bulkhead were replaced by 4B.A. swaged rods. This case is of interest since the loads in all the members except the heavy keel were found experimentally. The results, together with the theoretical figures, are given in Table II. and the agreement will be seen to be excellent. The figures in brackets are those which could not be measured directly and have been obtained by a consideration of the conditions of static balance at the joints of the frame.

Arising out of this experiment was another check upon the methods. In the analysis of R. & M. 800 the bulkhead bracing is taken to be rigid and in consequence the loads in the radial members of the D transverse frame could not be calculated. It was possible, however, to obtain the values of certain

differences in these loads, and as the loads were all found experimentally, the calculated and actual differences were compared. The result is given in Table III.

TABLE II.

Member.	Measured Load. lbs.	Correction for Balance. lbs.	Corrected Reading. lbs.	Calculated Load. lbs.	Difference. lbs.
A_1B_1	330.0	3.2	333.2	337.8	−4.6
A_2B_2	180.5	−1.0	179.5	177.3	+2.2
A_3B_3	−119.6	3.9	−115.7	−116.4	−0.7
A_4B_4			[−510.0]	−506.8	+3.2
A_1B_2	67.9		67.9	67.6	+0.3
A_2B_1	−27.5		−27.5	−28.0	−0.5
A_2B_3	102.5		102.5	100.8	+1.7
A_3B_2	−96.4		−96.4	−96.2	+0.2
A_3B_4	60.1		60.1	60.4	−0.3
A_4B_3	−74.4		−74.4	−74.0	+0.4
B_1B_2	−17.6	−4.0	−21.6	−20.0	+1.6
B_2B_3	−3.9	1.2	−2.7	−2.5	+0.2
B_3B_4	7.8	0.8	8.6	7.0	+1.6
B_1C_1	204.0	−6.4	197.6	202.4	−4.8
B_2C_2	109.1	0.9	110.0	106.4	+3.6
B_3C_3	−66.8	−0.9	−67.7	−69.6	+1.9
B_4C_4			[−306.0]	−304.0	+2.0
B_1C_2	60.7		60.7	59.6	+1.1
B_2C_1	−36.7		−36.7	−36.0	+0.7
B_2C_3	98.5		98.5	99.8	−1.3
B_3C_2	−97.4		−97.4	−96.8	+0.6
B_3C_4	63.1		63.1	63.0	+0.1
B_4C_3	−72.7		−72.7	−71.2	+1.5
C_1C_2	−7.8	−2.0	−9.8	−10.0	−0.2
C_2C_3	−3.9	4.0	0.1	−1.2	+1.3
C_3C_4	3.9	−0.5	3.4	3.5	−0.1
C_1D_1	70.6	−5.5	65.1	67.2	−2.1
C_2D_2	35.3	2.7	38.0	35.2	+2.8
C_3D_3	−19.6	−4.1	−23.7	−23.2	+0.5
C_4D_4			[−104.0]	−101.2	+2.8
C_1D_2	49.5		49.5	51.8	−2.3
C_2D_1	−42.3		−42.3	−43.8	−1.5
C_2D_3	99.2		99.2	98.8	+0.4
C_3D_2	−98.9		−98.9	−98.0	+0.9
C_3D_4	67.6		67.6	66.0	+1.6
C_4D_3	−68.4		−68.4	−68.6	−0.2
D_1D_2	−35.3	−2.0	37.3	−37.0	+0.3
D_2D_3	58.9	−0.5	58.4	59.0	−0.6
D_3D_4	161.0	4.0	165.0	166.0	−1.0
D_0D_1	65.3		65.3		
D_0D_2	3.5		3.5		
D_0D_3	−122.0		−122.0		
D_0D_4	191.8		191.8		

TABLE III.

Difference.	Measured Value. lbs.	Calculated Value. lbs.	Difference. lbs.
$D_0D_2 - D_0D_4$	−188.3	−187.6	−0.7
$D_0D_1 - D_0D_4$	−126.2	−126.5	−0.3

The agreement here is, within the limits of experimental accuracy, exact and gave confidence in the technique adopted.

(*b*) *The effect of varying the stiffness of the transverse frame bracing.*—The methods proposed by the Airship Stressing Panel for the calculation of the stresses in a braced tube were dependent upon the fact that the bulkhead to which the loads were applied did not distort under these loads. This result can be obtained in one of two ways: either the loads can be applied in a particular manner which will prevent such distortion or the bulkhead can be efficiently braced. In the experiment just described, which furnished a check on the accuracy of the methods adopted, the bulkhead was made as stiff as possible by radially bracing it with $\frac{5}{32}$in. diameter rods. It was now desired to discover what effect would be produced by modifying the stiffness of this bracing and the rods were replaced by 4B.A. swaged wires, the keel member being the same size as the other longitudinals.

The measured strains are given in Table IV., together with the theoretical values.

TABLE IV.

Single load of 400 lbs. on end bulkhead at D_4.

Member.	Load as Measured. lbs.	Calculated Load. lbs.	Difference. lbs.
A_1B_5	−75·5	−70.8	+4·7
A_5B_4	35·5	27.2	+8.3
A_5B_6	−103.7	−106.0	−2.3
A_6B_5	103.5	106.0	−2.5
A_6B_1	−26.7	−27.2	−0.5
A_1B_6	69.9	70.8	−0.9
B_4C_5	−70.5	−62.0	+8.5
B_5C_4	38.5	36.0	+2.5
B_5C_6	−103.5	−106.0	−2.5
B_6C_5	103.0	106.0	−3.0
B_6C_1	−40.6	−36.0	+4.6
B_1C_6	61.8	62.0	−0.2
C_4D_5	−59.6	−53·3	+6.3
C_5D_4	57·4	44.6	+12.8
C_5D_6	−102.8	−106.0	−3.2
C_6D_5	102.3	106.0	−3.7
C_6D_1	−44.6	−44.6	0
C_1D_6	50.0	53·3	−3·3

It will be seen that there are appreciable differences between the measured and theoretical loads in the members, the characteristic being that the loads in the wires of the top panels, that is, C_4D_5, C_5D_4, etc., are larger than calculated, while the loads of the remaining wires are smaller. This result is entirely in accord with the expected behaviour of the structure if the end bulkhead could distort.

It is evident from this experiment that if the results obtained from the application of the formulæ of R. & M. 800 are to be relied upon, the bulkhead bracing must be very efficient.

In the experiment just described the end bulkhead only was braced: in an actual airship structure the transverse frames would all have bracing of some sort and so another test was made in which all the bulkheads in the model structure were radially braced with 4B.A. rods. It was considered probable that while one elastic bulkhead might not be efficient in giving the theoretical distribu-

tion of loads, this result might be effected by two or more sets of transverse bracing. The results of this experiment are given in Table V.

It will be seen that in the bay between the bulkheads C and D there is a serious difference in all the members, between the actual and calculated loads, the panel $C_4D_4C_5D_5$ carrying much more than is indicated by theory and the other panels correspondingly less. Once the bulkhead C is passed, however, the measured and calculated loads agree well. It appears, therefore, that while one bulkhead radially wired with 4B.A. rods is insufficiently rigid to distribute the loads as required, such distribution is effected by two bulkheads similarly wired.

TABLE V.

Single load of 400 lbs. applied to joint D_4.

Member.	Measured Load. lbs.	Calculated Load. lbs.	Difference. lbs.
A_4B_5	−69.4	−70.8	−1.4
A_5B_4	27.5	27.2	+0.3
A_5B_6	−106.0	−106.0	0
A_6B_5	107.0	106.0	+1.0
A_6B_1	−27.2	−27.2	0
A_1B_6	71.4	70.8	+0.6
B_4C_5	−62.2	−62.0	+0.2
B_5C_4	39.1	36.0	+3.1
B_5C_6	−106.0	−106.0	0
B_6C_5	104.0	106.0	−2.0
B_6C_1	−38.2	−36.0	+2.2
B_1C_6	61.2	62.0	−0.8
C_4D_5	−70.4	−53.3	+17.1
C_5D_4	70.4	44.6	+25.8
C_5D_6	−99.5	−106.0	−6.5
C_6D_5	94.5	106.0	−11.5
C_6D_1	−41.3	−44.6	−3.3
C_1D_6	51.0	53.3	−2.3

(c) *Experiments upon the effect of a pyramidal nosepiece.*—When a braced tubular frame in which all the longitudinal members are the same size is subjected to a shear as in the experiments described, it was found by Mr. Southwell that the bulkheads remained plane after the load was applied. When the keel member, however, was of a different size from the other longitudinal members, this was not the case, and a distortion of the bulkheads out of their original plane occurred.

If it were possible to maintain the planarity of sections after loading, the methods of calculation not only become simpler but could be extended to the case of a tapering tube, such as occurs in an actual airship.

In the Report of the Airship Stressing Panel it was suggested that the pyramidal ends of an airship would tend to constrain the end sections to remain plane, and since there will be some section in the middle of the ship which will, from considerations of symmetry, also be plane, it was thought possible that solutions for the stress distribution based on the assumption that plane sections before loading remained plane afterwards, might approximate to the correct values.

Solutions of this type were therefore obtained for a uniform braced tube, these solutions being given as alternatives to those obtained when the assumption was made that the ends were free to distort.

The next experiments were therefore devised with the object of checking the efficacy of a pyramidal nosepiece in maintaining planarity of sections.

These experiments were conducted in an exactly similar manner to those already described, but the structure was provided with a pyramidal end made of tubes $\frac{3}{8}$in. O.D. × 22g. This structure is shown in Figs. 1 and 2. The experimental values of the loads in all cases gave very good results when the usual checks were applied, *i.e.*, corresponding members on opposite sides gave practically the same readings, and the components in the wires gave the correct shear across the section.

Departures from theoretical conditions, which might be expected to cause differences between theoretical and actual values of the loads, were as follows:—

(i.) In the theoretical investigations the bulkheads are assumed to be rigid in their own planes. The effect of such lack of rigidity was examined experimentally, by substituting heavier bracing in the end frame, and by bracing all transverse frames as in earlier experiments.

(ii.) The loads applied to the nodes of the transverse frame to maintain planarity, are required to be of definite amount; the nosepiece will not necessarily effect the correct distribution although the resultant axial force will be zero as required.

(iii.) Since these loads are not applied as assumed, the stresses in the members will be subject to local disturbances, and although the applicability of St. Venant's principle to a redundant frame of this sort has been demonstrated,* the redistribution of stresses requires a long tube in which to become operative. In the three experiments with the nosepiece in position, the experimental values are compared with the theoretical values for the tube fixed at one end with the loaded end free to warp, and also with those when the transverse frames are constrained to remain plane.

Experiment I.—Keel member $\frac{3}{8}$in. solid steel. All other longitudinal members $\frac{3}{8}$in. O.D. × 22g. Each bulkhead radially braced with 4 B.A. swaged rods. No bulkhead bracing in remaining transverse frames. Pyramidal nosepiece in position.

Single load of 400lbs. applied at joint D_4.

The results are given in Table 6, where the differences between the measured values and the two sets of theoretical values are tabulated.

It will be seen that in nearly every case the measured loads are nearer the values for the free ended tube, and in only two cases does the measured load lie between the two theoretical results. One source of discrepancy was undoubtedly the distortion of the transverse frame due to the elasticity of its bulkhead bracing, and another experiment was carried out in which all the bulkheads were braced.

Experiment II.—Structure as in Experiment I., but all bulkheads radially braced with 4 B.A. swaged rods.

The results are given in Table VII., in the same form as for Experiment I.

In the panels between the bulkheads D and C all the loads are nearer the free end calculations and none lie between the two theoretical results. In each of the bays C – B, B – A two members are nearer the constrained end figures, and three loads lie between the theoretical results.

Experiment III.—Structure as in Experiment I., but end bulkhead braced with $\frac{3}{8}$in. solid bars and no bulkhead bracing in the other transverse frames.

The results are given in Table VIII., as for Experiments I. and II.

* *Phil. Mag.*, January, 1923. Southwell.

In the bay D – C one member shows a load lying nearer the constrained condition calculations and two members have loads lying between the theoretical values. In the bay C – B four loads are closer the constrained than the free values, and four members give loads lying between the theoretical values. In the bay B – A four loads also lie nearer the constrained end values, but only two lie between the two sets of calculated results.

TABLE VI.

Member	Measured Load. lbs.	Calculated Load. lbs. End Constrained.	Calculated Load. lbs. End Free.	Difference. End Constrained.	Difference. End Free.
A_4B_5	−75·5	−55·0	−74·0	20.5	1·5
A_5B_4	57·1	49·9	60.4	7·2	−3·3
A_5B_6	−99·0	−98·0	−96.2	1.0	+2.8
A_6B_5	100.0	111.7	100.8	−11.7	−0.8
A_6B_1	−21.9	−36.2	−28.0	−14·3	−7·1
A_1B_6	75·0	68.2	67.6	6.8	7·4
B_4C_5	−83.2	−54·0	−71.2	29.2	12.0
B_5C_4	66.9	50.9	63.0	16.0	3·9
B_5C_6	−101.0	−100.8	−96.8	0.2	4.2
B_6C_5	98.0	109.0	99.8	−11.0	−1.8
B_6C_1	−31.1	−42·7	−36.0	−11.6	−4.9
B_1C_6	47·9	62.2	59.6	−14·3	−11·7
C_4D_5	−75·5	−53·0	−68.6	22·5	6.9
C_5D_4	77·5	51.9	66.0	25.6	11·5
C_5D_6	−94.4	−103·5	−98.0	−9·1	−3.6
C_6D_5	102.0	106.2	98.8	−4.2	+3·2
C_6D_1	−34·7	−49·2	−43.8	−14·5	−9·1
C_1D_6	47·4	55·7	51.8	−8.3	−4·4

TABLE VII.

Member.	Measured Load. lbs.	Calculated Load. lbs. End Constrained.	Calculated Load. lbs. End Free.	Difference. End Constrained.	Difference. End Free.
A_4B_5	−71·9	−55·0	−74·0	16.9	−2.1
A_5B_4	50.0	49.9	60.4	0.1	−10.4
A_5B_6	−104.0	−98.0	−96.2	6.0	7.8
A_6B_5	104.0	111.7	100.8	−7·7	3·2
A_6B_1	−20.4	−36.2	−28.0	−15.8	−7.6
A_1B_6	64.4	68.2	67.6	−3.8	−3·2
B_4C_5	−70.9	−54·0	−71.2	16.9	−0.3
B_5C_4	52.0	50.9	63.0	1.1	−11.0
B_5C_6	−103.0	−100.8	−96.8	2.2	6.2
B_6C_5	101.0	109.0	99.8	−8.0	1.2
B_6C_1	−29.6	−42·7	−36.0	−13.1	−6.4
B_1C_6	59.1	62.2	59.6	−3·1	−0.5
C_4D_5	−82.6	−53·0	−68.6	29.6	14.0
C_5D_4	84.6	51.9	66.0	32.7	18.6
C_5D_6	−91.9	−103·5	−98.0	−11.6	−6.1
C_6D_5	94.0	106.2	98.8	−12.2	−4.8
C_6D_1	−37.8	−49·2	−43.8	−11.4	−6.0
C_1D_6	51.0	55·7	51.8	−4·7	−0.8

It was found in this experiment that when the transverse frame was approximately rigid in its own plane, the loads induced in the members of the nosepiece were sufficient to cause some of them to bow. This bowing is equivalent to a reduction in the modulus of elasticity of a serious amount,* and this in turn

* Aeronautical Research Committee. R. & M. 792. Pippard.

will modify the load distribution on the nodes of the end transverse. It is thus clear that for effective restraint a very stiff nose structure is necessary as well as a very nearly rigid transverse frame.

TABLE VIII.

Member.	Measured Load. lbs.	Calculated Load. lbs. End Constrained.	Calculated Load. lbs. End Free.	Difference. End Constrained.	Difference. End Free.
A_4B_5	−61.1	−55.0	−74.0	6.1	−12.9
A_5B_4	39.8	49.9	60.4	−11.1	−20.6
A_5B_6	−109.5	−98.0	−96.2	11.5	13.2
A_6B_5	108.0	111.7	100.8	−3.7	7.2
A_6B_1	−27.5	−36.2	−28.0	−8.7	−0.5
A_1B_6	62.2	68.2	67.6	−6.0	−5.4
B_4C_5	−66.2	−54.0	−71.2	12.2	−5.0
B_5C_4	49.0	50.9	63.0	−1.9	−14.0
B_5C_6	−99.0	−100.8	−96.8	−1.8	2.2
B_6C_5	107.0	109.0	99.8	−2.0	7.2
B_6C_1	−33.6	−42.7	−36.0	−9.1	−2.4
B_1C_6	61.2	62.2	59.6	−1.0	1.6
C_4D_5	−66.3	−53.0	−68.6	13.3	−2.3
C_5D_4	68.3	51.9	66.0	16.4	2.3
C_5D_6	−97.0	−103.5	−98.0	−6.5	−1.0
C_6D_5	103.0	106.2	98.8	−3.2	4.2
C_6D_1	−39.8	−49.2	−43.8	−9.4	−4.0
C_1D_6	51.0	55.7	51.8	−4.7	−0.8

(*d*) *The effect of torsion on a braced tube.*—The theoretical analysis for the stresses in a braced tube when subjected to a pure torque,* indicates that the panel bracing members alone are brought into operation, and no stresses are put into the longitudinal members or transverse struts.

As in the theoretical investigation for the stress distribution in a tube subjected to shear, it is assumed that the external loading is applied in the particular manner which prevents any distortion of the transverse frame, and also that the structure is pin-jointed throughout. Transverse frames which were plane before loading, are then shown to remain plane in the strained condition of the structure.

The following experiments were carried out to determine the degree of accuracy obtained in an actual structure compared with calculations based on the above analysis, and also to discover the effect of varying the elasticity of the bulkhead bracing in the transverse to which the torque was applied, when the external loading, although giving a resultant pure torque, was not applied to the joints as assumed in the analysis.

The structure used was the hexagonal frame already described, fitted with a solid $\frac{3}{8}$in. diameter steel " keel " member and no pyramidal nosepiece.

The torque was applied by loads at the joints D_3 and D_6 into which special swivel hooks were screwed. An upward load was applied at D_3 by means of the weighing balance used in the shearing force experiments, and weights were hung from D_6 (Fig. 6). An initial load was applied to D_6 equal to the weight of the scale pan.

The methods adopted in the experiments were exactly as described in the earlier work.

The increment of load in each case was 280lbs. upward at D_3, and 280lbs. downwards at D_6, giving a torque of 12,124 inch-lbs.

* Aeronautical Research Committee. R. & M. 791. Southwell.

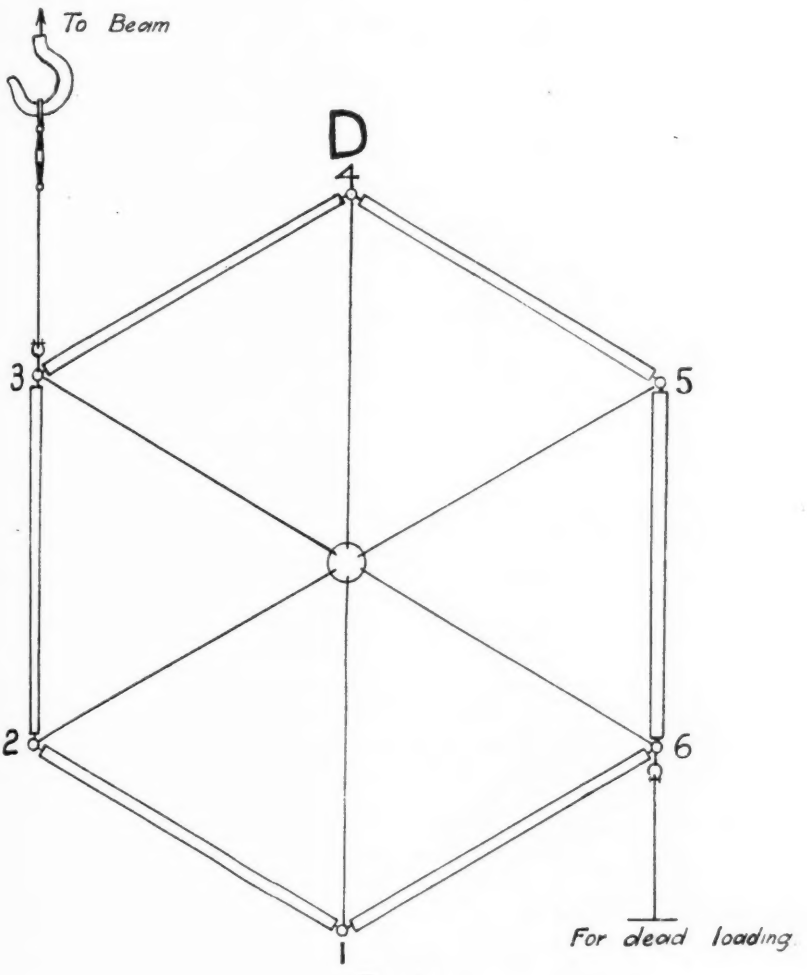

FIG. 6.

In the first experiment the end bulkhead was braced with $\frac{3}{8}$in. solid rods, the remaining bulkheads being unbraced. This reproduced as nearly as possible the assumptions made in the theoretical investigation, since the nearly rigid bracing serves to distribute the loads in a manner corresponding to that required by the analysis.

The theoretical load in each of the panel wires is 72.8lbs., and the closeness of the experimental results to this will be seen from Table IX., which gives the measured loads in all these members.

There are small departures from the theoretical figures, but these balance each other as will be seen from the average load in the wires of each bay.

In bay A B. Average load = 72.54lbs.
In bay B C. Average load = 73.58lbs.
In bay C D. Average load = 72.38lbs.

TABLE IX.

Member.	Measured Load. lbs.	Member.	Measured Load. lbs.
A_1B_2	74·5	A_4B_5	71·5
A_2B_1	−71·5	A_5B_4	−72·5
A_2B_3	74·5	A_5B_6	72·5
A_3B_2	−70·5	A_6B_5	−71·5
A_3B_4	72·5	A_6B_1	73·5
A_4B_3	−72·0	A_1B_6	−73·5
B_1C_2	74·5	B_4C_5	71·5
B_2C_1	−73·5	B_5C_4	−72·5
B_2C_3	72·5	B_5C_6	73·5
B_3C_2	−74·5	B_6C_5	−74·5
B_3C_4	75·5	B_6C_1	73·5
B_4C_3	−73·5	B_1C_6	−73·5
C_1D_2	73·5	C_4D_5	74·5
C_2D_1	−70·5	C_5D_4	−71·0
C_2D_3	70·5	C_5D_6	71·5
C_3D_2	−73·5	C_6D_5	−71·5
C_3D_4	71·0	C_6D_1	74·0
C_4D_3	−73·5	C_1D_6	−73·5

In order to determine the effect of a less rigid bulkhead upon the stress distribution, this experiment was repeated with 4 B.A. rods taking the place of the $\frac{5}{8}$in. solid radial members. This substitution, however, had very little effect upon the results as will be seen from the figures in Table X.

The average loads also show the same degree of accuracy as previously.

In bay A B. Average load = 72.92lbs.
In bay B C. Average load = 72.83lbs.
In bay C D. Average load = 73.04lbs.

TABLE X.

Member.	Measured Load. lbs.	Member.	Measured Load. lbs.
A_1B_2	71·5	A_4B_5	73·5
A_2B_1	−73·5	A_5B_4	−72·0
A_2B_3	72·0	A_5B_6	73·0
A_3B_2	−74·5	A_6B_5	−73·5
A_3B_4	71·0	A_6B_1	73·5
A_4B_3	−75·5	A_1B_6	−71·5
B_1C_2	74·5	B_4C_5	74·5
B_2C_1	−71·0	B_5C_4	−73·5
B_2C_3	74·5	B_5C_6	71·5
B_3C_2	−73·5	B_6C_5	−74·5
B_3C_4	71·5	B_6C_1	71·5
B_4C_3	−73·0	B_1C_6	−70·5
C_1D_2	74·5	C_4D_5	73·0
C_2D_1	−70·5	C_5D_4	−72·5
C_2D_3	75·5	C_5D_6	74·5
C_3D_2	−71·5	C_6D_5	−73·5
C_3D_4	71·5	C_6D_1	73·5
C_4D_3	−74·5	C_1D_6	−71·5
D_6D_4	10.2	D_6D_5	−81.6
D_6D_6	104.5		

In the next experiment the whole of the transverse bracing was omitted, and the results are given in Table XI. It will be seen that in this case the greater

part of the load is transmitted through the vertical panels in the planes of the applied loads.

The structure in the experiment underwent considerable distortion, and the average loads in each panel are not so near to the theoretical value of 72.8lbs., as in the previous experiments. This follows as a direct result of the distortion.

In bay A B. Average load = 79.3lbs.
In bay B C. Average load = 77.7lbs.
In bay C D. Average load = 77.0lbs.

TABLE XI.

Member.	Calculated Load. lbs.	Member.	Measured Load. lbs.
A_1B_2	73·5	A_4B_5	76·5
A_2B_1	35·7	A_5B_4	33·7
A_2B_3	226.2	A_5B_6	226.2
A_3B_2	− 166.1	A_6B_5	− 172.2
A_3B_4	6.1	A_6B_1	6.1
A_4B_3	− 34·7	A_1B_6	− 33·7
B_1C_2	33·7	B_4C_5	33·7
B_2C_1	− 4.1	B_5C_4	− 1.0
B_2C_3	206.0	B_5C_6	208.0
B_3C_2	− 202.0	B_6C_5	− 205.0
B_3C_4	− 9.2	B_6C_1	− 7.1
B_4C_3	− 30.6	B_1C_6	− 24.5
C_1D_2	18.4	C_4D_5	17·3
C_2D_1	− 4.1	C_5D_4	− 2.0
C_2D_3	212.0	C_5D_6	215.0
C_3D_2	− 201.0	C_6D_5	− 203.0
C_3D_4	9.2	C_6D_1	10.2
C_4D_3	− 16.3	C_1D_6	− 15·3

(*e*) *The effect of altering the distribution of external forces.*—In the work already described, the external load system consisted in each case of a single load acting vertically on the joint D_4 except in the experiments upon the torsional stresses.

In an actual case the load will be distributed in a complicated manner between the various nodes of a transverse frame. It was therefore of considerable importance to determine whether the stress distribution was dependent only upon the resultant action on the frame, or whether the actual distribution of the external loading system affected such stresses. In the case of a homogeneous elastic solid the stress distribution is practically independent of the manner in which the external load is applied except in the immediate neighbourhood of the loading points, this being the well-known Principle of Saint Venant.*

During the course of the theoretical investigations initiated by the Airship Stressing Panel, it appeared probable that the scope of the Principle might be extended to the case of certain braced frameworks, and a general demonstration of the validity of this assumption was provided by Southwell.† The methods of stress analysis suggested by the Airship Stressing Panel,‡ by which the forces in the various members of a braced tube may be obtained in terms of the resultant actions at the section considered, depend entirely for their validity upon the applicability of St. Venant's Principle to such a structure.

In the case of a simply stiff framework, *i.e.*, one in which there are just sufficient bars to maintain the geometry of the structure, the internal stress

* *Mathematical Theory of Elasticity*, A. E. H. Love, 3rd Ed., p. 129.
† *Phil. Mag.*, January, 1923.
‡ R. & M. 800.

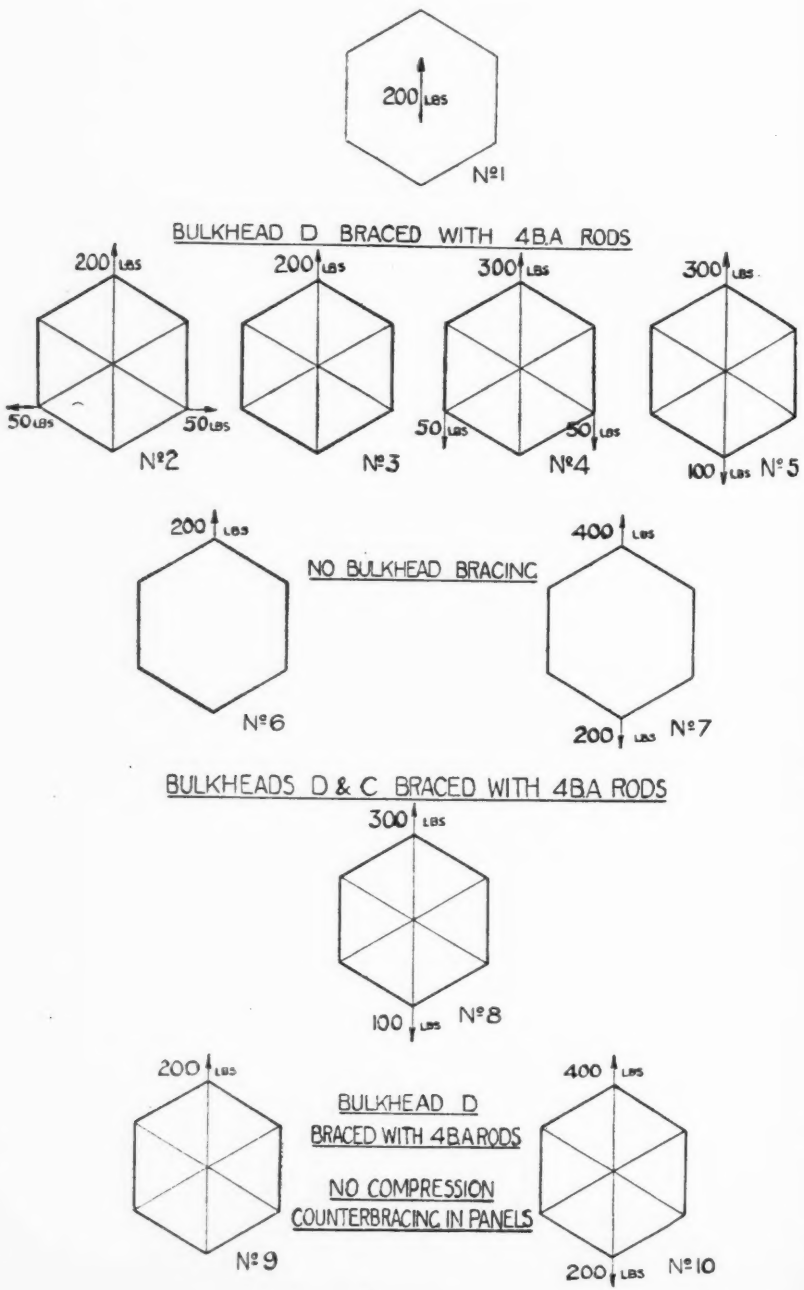
200 LBS
Nº1
BULKHEAD D BRACED WITH 4B.A RODS
200 LBS
50 LBS
50 LBS
Nº2
200 LBS
Nº3
300 LBS
50 LBS
50 LBS
Nº4
300 LBS
100 LBS Nº5
200 LBS
NO BULKHEAD BRACING
Nº6
400 LBS
200 LBS Nº7
BULKHEADS D & C BRACED WITH 4B.A RODS
300 LBS
100 LBS Nº8
200 LBS
BULKHEAD D
BRACED WITH 4B.A RODS
NO COMPRESSION
COUNTERBRACING IN PANELS
Nº9
400 LBS
200 LBS Nº10

FIG. 7.

distribution under any external load system is governed only by the configuration of the framework, and the stresses in a particular member may vary very considerably under the action of load systems which are statically equivalent. It is therefore clear that the Principle of St. Venant is not applicable to this class of framework: it is only when the stress distribution becomes a function of the elastic properties of the framework that it can operate. This essential condition is fulfilled by a redundant structure, but since the degree of redundancy may range from a single member more than the number required for stiffness to an infinite number in the extreme case of a solid body, it is clearly a matter of great importance to determine the effect of the number and disposition of redundancies upon the operation of the Principle and the experiments to be described were designed to this end.

The structure used was the same as that already described, the $\frac{7}{8}$in. solid keel member being used.

Since it was desired to show, if possible, the effect of the disposition and number of redundancies, the experiments were divided into four sets as follows:—

Set No. 1.—All bulkheads unbraced; all panels counterbraced.

Set No. 2.—Bulkhead D radially braced with 4B.A. rods; all panels counterbraced.

Set No. 3.—Bulkheads C and D radially braced with 4B.A. rods; all panels counterbraced.

Set No. 4.—Bulkhead D radially braced with 4B.A. rods; compression counterbracing members omitted from all panels.

The scheme of the experiments and diagram of the load systems is shown in Fig. 7, the net shear being 200 lbs. in each case.

On this diagram No. 1 is the theoretical case, the stresses being calculated by the methods of R. & M. 800, Appendix V. The assumptions made in this calculation are that the D bulkhead bracing is rigid and that the transverse struts are rigid throughout the structure. The second assumption has very little effect upon the stress distribution and may be neglected.

The stress distribution throughout the tube will be the same whether the end bulkhead D be considered rigid or whether it be considered unbraced with the external load system applied in a particular but unspecified manner. For this reason it has been taken as a reference case in the first three sets of experiments.

Nos. 2-5 on the diagram show the load systems adopted in Set No. 2, these being the experiments actually carried out first. The greatest variations from the theoretical case were given by No. 5, and so for Set No. 1 the loadings Nos. 6 and 7 on the diagram were taken.

For Set No. 3 only one case (No. 8 on the diagram) was measured for comparison with No. 1.

Nos. 9 and 10 illustrate the loadings adopted for the experiments of Set No. 4.

Set No. 1. *All bulkheads unbraced; all panels counterbraced.*—The loads in the wires as measured and those in the longitudinals obtained from these are given in Table XII. for load systems Nos. 6 and 7 on the chart.

It is evident at once that a load applied to the top joint of the structure as in load system No. 6 tends to stress mainly the members in the top panels and in a length of three bays very little is transmitted to the bottom panels.

This effect is also seen by comparing the loads in the top panels (3-4) for the two cases Nos. 6 and 7. In load system No. 7 there is 400 lbs. at the top joint compared with 200 lbs. in load system No. 6 and the stresses in the top panels are approximately doubled. These are set out again in Table XIII. for easy reference.

TABLE XII.

Member.	Measured Loads. No. 6.	No. 7.	Theoretical Loads. No. 1.
C_1D_1	nil	−228.4	33.6
C_2D_2	−2.8	85.6	17.6
C_3D_3	102.6	199.0	−11.6
C_4D_4	−211.6	−424.2	−50.6
C_1D_2	3.6	−125.4	25.9
C_2D_1	nil	148.8	−21.9
C_2D_3	10.6	27.6	49.4
C_3D_2	nil	14.0	−49.0
C_3D_4	137.6	276.0	33.0
C_4D_3	−144.0	−286.0	−34.3
B_1C_1	5.6	−578.4	101.2
B_2C_2	15.0	300.0	53.2
B_3C_3	263.4	530.0	−34.8
B_4C_4	−633.2	−1268.8	−152.0
B_1C_2	−5.2	−128.0	29.8
B_2C_1	nil	102.4	−18.0
B_2C_3	32.6	64.0	49.9
B_3C_2	−7.4	25.6	−48.4
B_3C_4	130.0	263.2	31.5
B_4C_3	−104.6	−204.4	−35.6
A_1B_1	−2.4	−918.8	168.9
A_2B_2	41.4	481.2	88.6
A_3B_3	378.8	812.0	−58.2
A_1B_4	−1001.2	−1996.2	−253.4
A_1B_2	−12.6	−132.6	33.8
A_2B_1	nil	93.6	−14.0
A_2B_3	62.4	104.0	50.4
A_3B_2	11.0	63.2	−48.1
A_3B_4	134.6	269.6	30.2
A_4B_3	−89.8	−181.6	−37.0

TABLE XIII.

Member.	Load System 6. Load.	(Load) × 2	Load System 7. Load.
C_3D_3	102.6	205.2	199.0
C_4D_4	−211.6	−423.2	−424.2
C_3D_4	137.6	275.2	276.0
C_4D_3	−144.0	−288.0	−286.0
B_3C_3	263.4	526.8	530.0
B_4C_4	−633.2	−1266.4	−1268.8
B_3C_4	130.0	260.0	263.2
B_4C_3	−104.6	−209.2	−204.4
A_3B_3	378.8	757.6	812.0*
A_4B_4	−1001.2	−2002.4	−1998.0
A_3B_4	134.6	269.2	268.0
A_4B_3	−89.8	−179.6	−181.6

On further comparison, the stresses in the members of the bay AB for the three load systems Nos. 6, 7 and 1 show very little tendency to converge.

It would appear, therefore, that in a framed tube in which all panels are redundantly braced, but in which there is no bracing in the plane of the applied

* This member shows a greater discrepancy because it is the first to be affected appreciably by the variation in the stresses in the 2—3 panel wires.

load system, the operation of the St. Venant Principle, even if it exists, is a very slow process.

Set No. 2. Bulkhead D radially braced with 4B.A. rods; all panels counter-braced.—The various load systems applied in this case are shown in the diagrams Nos. 2-5. Of these the stresses for No. 3 had already been obtained in the earlier experiments, but all the others entailed new measurements. The stresses as measured and those calculated for No. 1 are given in Table XIV.

TABLE XIV.

	Calculated Load. lbs.		Measured Load. lbs.		
Member.	1	2	3	4	5
C_1D_1	33.6	35.1	32.5	36.3	21.6
C_2D_2	17.6	18.0	19.0	15.1	27.3
C_3D_3	−11.6	−12.2	−11.8	−9.2	−8.2
C_4D_4	−50.6	−50.8	−52.0	−54.9	−63.4
C_1D_2	25.9	26.0	24.7	25.8	14.5
C_2D_1	−21.9	−22.8	−21.1	−23.6	−14.0
C_2D_3	49.4	49.7	49.6	49.6	51.0
C_3D_2	−49.0	−49.4	−49.4	−45.4	−50.0
C_3D_4	33.0	33.0	33.8	35.7	41.2
C_4D_3	−34.3	−33.8	−34.2	−37.6	−40.3
B_1C_1	101.2	102.6	98.8	101.2	65.8
B_2C_2	53.2	54.0	55.0	50.3	73.0
B_3C_3	−34.8	−35.7	−33.8	−24.4	−22.7
B_4C_4	−152.0	−149.4	−153.0	−165.8	−177.4
B_1C_2	29.8	29.9	30.3	27.3	26.5
B_2C_1	−18.0	−17.9	−18.3	−16.4	−14.2
B_2C_3	49.9	49.2	49.2	50.1	50.0
B_3C_2	−48.4	−49.9	−48.7	−47.1	−49.0
B_3C_4	31.5	31.0	31.6	34.4	33.8
B_4C_3	−35.6	−35.0	−36.3	−40.1	−40.0
A_1B_1	168.9	170.0	166.6	161.0	123.4
A_2B_2	88.6	91.0	89.7	88.7	113.2
A_3B_3	−58.2	−60.7	−57.8	−40.5	−42.0
A_4B_4	−253.4	−248.7	−255.0	−280.8	−283.8
A_1B_2	33.8	33.4	33.9	33.4	33.8
A_2B_1	−14.0	−13.9	−13.7	−11.6	−10.9
A_2B_3	50.4	49.7	51.2	48.0	50.3
A_3B_2	−48.1	−50.2	−48.2	−49.6	−50.2
A_3B_4	30.2	29.5	30.0	34.6	29.2
A_4B_3	−37.0	−36.1	−37.2	−39.8	−40.4

To show the variation in the stresses more clearly, the differences from the theoretical case have been calculated and are given in Table XV.

In the discussion of the accuracy of the experimental results, it was stated that repeat readings on the wires could be made to within ±1 lb., so that it may be assumed that any variation within these limits can be neglected.

With the load system No. 2 only two wires out of eighteen measured show variations outside these limits, and in the case of load system No. 3 only one out of the eighteen exceeds 1 lb., and this only by 0.2 lb.

It may be assumed, therefore, that within the limits of experimental accuracy the load systems Nos. 2 and 3 give stresses agreeing throughout with the theoretical case No. 1.

With the load system No. 4 the variations are large, but corrections of ±1 lb. to the readings have such a considerable effect that deductions from this case are inconclusive.

TABLE XV.

Member.	No. 2.	No. 3.	No. 4.	No. 5.
C_1D_1	1.5	−1.1	2.7	−12.0
C_2D_2	0.4	1.4	−2.5	9.7
C_3D_3	0.6	0.2	−2.4	−3.4
C_4D_4	0.2	1.4	4.3	12.8
C_1D_2	0.1	−1.2	−0.1	−11.4
C_2D_1	0.9	−0.8	1.7	−7.9
C_2D_3	0.3	0.2	0.2	1.6
C_3D_2	0.4	0.4	−3.6	1.0
C_3D_4	0	0.8	2.7	8.2
C_4D_3	−0.5	−0.1	3.3	6.0
B_1C_1	1.4	−2.4	0	−35.4
B_2C_2	0.8	1.8	−2.9	19.8
B_3C_3	0.9	−1.0	−10.4	−12.1
B_4C_4	−2.6	1.0	13.8	25.4
B_1C_2	0.1	0.5	−2.5	−3.3
B_2C_1	−0.1	0.3	−1.6	−3.8
B_2C_3	−0.7	−0.7	0.2	0.1
B_3C_2	1.5	0.3	−1.3	0.6
B_3C_4	−0.5	0.1	2.9	2.3
B_4C_3	−0.6	0.7	4.5	4.4
A_1B_1	1.1	−2.3	−7.9	−45.5
A_2B_2	2.4	1.1	0.1	24.6
A_3B_3	2.5	−0.4	−17.7	−16.2
A_1B_4	−4.7	1.6	27.4	30.4
A_1B_2	−0.4	0.1	−0.4	0
A_2B_1	−0.1	−0.3	−2.4	−3.1
A_2B_3	−0.7	0.8	−2.4	−0.1
A_3B_2	2.1	0.1	1.5	2.1
A_3B_4	−0.7	−0.2	4.4	−1.0
A_4B_3	−0.9	0.2	2.8	3.4

With load system No. 5, however, the variations from No. 1 are much more marked and the figures obtained have therefore been selected for detailed analysis.

In Table XVI. the variation of the stresses from those due to load system No. 1 are given as percentages of the latter. The members are arranged in groups of three, each group consisting of the corresponding members in the three bays. Variations of 1 lb. or less are neglected.

It will be seen that there are ten groups of corresponding members, and in seven of these groups there is a progressive drop in the percentage variation of stress from the bay CD to the bay AB. In two of the remaining three groups (the 3-3 and 2-1) the figure for the bay BC does not lie between those for the other bays, although the variation is less in AB than in CD. Corrections of less than 1 lb. to the readings of one member in each group would, however, cause those two groups to show a progressive drop.

The only remaining group (3-2) can similarly be adjusted by corrections of less than 1 lb. to the readings.

Hence seven of the groups show a progressive diminution of percentage variation without any correction of the experimental results, while adjustments of the remaining three by amounts within the limits of experimental accuracy would cause those to show a similar progression. Of the experiments in this set, therefore, the stresses for Nos. 2 and 3 agree almost exactly with those for No. 1, while No. 5 shows that there is a distinct tendency towards the equalisation of stresses when bracing is provided in the plane of the external load system.

Set No. 3. Bulkheads C and D radially braced with 4B..1. rods; all panels counterbraced.—Since in Set No. 2 the load system No. 5 gave the greatest variation from the theoretical case, the same loading was adopted for the present set of experiments in which the two bulkheads C and D were radially braced.

The loads for this case are given in Table XVII. together with the variation from those of No. 1 as before, variations of less than 1 lb. being neglected.

In this set of experiments the loads afford very definite evidence of the rapid equalisation of stresses. In five out of the six wires in the CD bay the variation between the two systems of loading is considerable, but in the bay AB the variation has been reduced to negligible dimensions in every case, and even in the bay BC four of the six wires show negligible variation.

TABLE XVI.

Member.	Load. No. 1.	Load. No. 5.	Variation of No. 5 from No. 1. lbs.	Variation of No. 5 from No. 1. Per cent. of No. 1.
C_1D_1	33.6	21.6	−12	−35.7
B_1C_1	101.2	65.8	−35.4	−35.0
A_1B_1	168.9	123.4	−45.5	−27.0
C_2D_2	17.6	27.3	9.7	55.0
B_2C_2	53.2	73.0	19.8	37.2
A_2B_2	88.6	113.2	24.6	27.6
C_3D_3	−11.6	−8.2	−3.4	−29.3
B_3C_3	−34.8	−22.7	−12.1	−34.8
A_3B_3	−58.2	−42.0	−16.2	−27.8
C_4D_4	−50.6	−63.4	12.8	25.3
B_4C_4	−152.0	−177.4	25.4	16.7
A_4B_4	−253.4	−283.8	30.4	12.0
C_1D_2	25.9	14.5	−11.4	−44.0
B_1C_2	29.8	26.5	−3.3	−11.0
A_1B_2	33.8	33.8	0	0
C_2D_1	−21.9	−14.0	−7.9	−36.0
B_2C_1	−18.0	−14.2	−3.8	−21.1
A_2B_1	−14.0	−10.9	−3.1	−22.1
C_2D_3	49.4	51.0	1.6	3.2
B_2C_3	49.9	50.0	—	—
A_2B_3	50.4	50.3	—	—
C_3D_2	−49.0	−50.0	—	—
B_3C_2	−48.4	−49.0	—	—
A_3B_2	−48.1	−50.2	2.1	4.3
C_3D_4	33.0	41.2	8.2	24.8
B_3C_4	31.5	33.8	2.3	7.3
A_3B_4	30.2	29.2	—	—
C_4D_3	−34.3	−40.3	6.0	17.5
B_4C_3	−35.6	−40.0	4.4	12.3
A_4B_3	−37.0	−40.4	3.4	9.2

TABLE XVII.

Member.	Loads. No. 1.	Loads. No. 8.	Variation from No. 1. Actual.	Variation from No. 1. Per cent. of No. 1
C_1D_1	33.6	22.8	−10.8	−32.2
B_1C_1	101.2	84.2	−17.0	−16.8
A_1B_1	168.9	151.0	−17.9	−10.6
C_2D_2	17.6	16.5	−1.1	−6.2
B_2C_2	53.2	55.5	2.3	4.3
A_2B_2	88.6	90.3	1.7	1.9
C_3D_3	−11.6	1.0	−12.6	−108.6
B_3C_3	−34.8	−4.2	−30.6	−88.0
A_3B_3	−58.2	−28.4	−29.8	−51.2
C_4D_4	−50.6	−75.7	25.1	49.5
B_4C_4	−152.0	−197.5	45.5	30.0
A_4B_4	−253.4	−297.7	44.3	17.5
C_1D_2	25.9	19.3	−6.6	−25.4
B_1C_2	29.8	30.3	—	—
A_1B_2	33.8	33.7	—	—
C_2D_1	−21.9	−14.8	−7.1	−32.4
B_2C_1	−18.0	−20.6	2.6	+14.4
A_2B_1	−14.0	−13.1	—	—
C_2D_3	49.4	47.8	−1.6	−3.2
B_2C_3	49.9	50.7	—	—
A_2B_3	50.4	50.9	—	—
C_3D_2	−49.0	−40.8	−8.2	−16.7
B_3C_2	−48.4	−48.1	—	—
A_3B_2	−48.1	−48.8	—	—
C_3D_4	33.0	49.2	16.2	49.1
B_3C_4	31.5	30.1	−1.4	−4.5
A_3B_4	30.2	29.5	—	—
C_4D_3	−34.3	−49.1	14.8	43.2
B_4C_3	−35.6	−35.6	—	—
A_4B_3	−37.0	−37.4	—	—

The introduction of an extra bulkhead bracing system has therefore caused the strain equalisation to take place much more quickly than is indicated by the results of the experiments of Set No. 2.

Set No. 4. Bulkhead D radially braced with 4B.I. rods; compression counterbracing members omitted from all panels.—In this set of experiments the compressive counterbracing members in all panels were omitted, so that apart from the D bulkhead bracing there were no redundancies in the framework. The two load systems are shown in the diagram as Nos. 9 and 10, and Table XVIII. gives the stresses obtained for the two cases. The theoretical stress distribution which would be obtained with a rigid bulkhead or alternatively for a special arrangement of the external load is also given in Table XVIII. for comparison.

TABLE XVIII.

Member.	Loads. Theoretical.	No. 9.	No. 10.
C_1D_1	0	0	0
B_1C_1	78.0	78.4	73.6
A_1B_1	156.0	154.0	142.2
C_2D_2	−39.0	−39.2	−36.8
B_2C_2	−1.5	−1.0	0.3
A_2B_2	36.0	39.6	41.4
C_3D_3	−76.5	−76.0	−71.4
B_3C_3	−105.0	−104.0	−87.9
A_3B_3	−133.5	−133.7	−111.1
C_4D_4	−96.0	−102.2	−121.6
B_4C_4	−192.0	−195.4	−227.2
A_1B_4	−283.0	−294.2	−330.6
C_1D_2	50.5	51.0	47.8
B_1C_2	50.5	49.2	44.6
A_1B_2	50.5	50.0	47.0
C_2D_3	99.5	98.8	92.8
B_2C_3	99.5	102.8	100.4
A_2B_3	99.5	99.2	98.8
C_3D_4	62.5	66.4	79.0
B_3C_4	62.5	60.6	68.6
A_3B_4	62.5	64.4	67.2

It will be noticed that the stresses in the three cases of this set are in reasonably good agreement in spite of the redundancies being confined to the loaded bulkhead. The tube was insufficiently long to allow definite conclusions to be drawn as to the applicability of the Principle of St. Venant to this case, but comparing the results obtained with those of Set No. 1, where all the redundancies were in the panel bracing, it is evident that redundant bracing when in the plane of the bulkhead is far more efficient than when placed in the panels in conducing to an equalisation of stresses.

Conclusions

The following conclusions may be drawn from the foregoing experiments :—

1. When a tubular framework with redundant bracing is provided with efficient bracing in the plane of the applied load system, the stresses in the members tend quickly to become independent of the arrangement of the load system.

2. The provision of additional bracing in other planes parallel to that of loading produces a much quicker equalisation of stresses.

3. Unless efficient bracing is provided in the plane of loading to act as an initial distributor of the external load, even if the tube exhibits a high degree of redundancy in other planes, the process of equalisation is a very slow one, and the stresses even at a distance from the plane of loading would be dependent to a considerable extent upon the arrangement of the load system.

4. If in the design of such structures (*e.g.*, the hull of a rigid airship) formulæ are used which determine the stresses in the members in terms only of

the resultant actions at the section considered, it is important that effective bracing should be provided in the plane of the load system. Unless this is done there is a very serious liability of error.

The Effect of Non-Operation of Certain Members in the Framework

In some cases, members of a framework are capable of resisting compression only up to a definite value, *e.g.*, if they are slender struts or initially tensioned wires. In the case of a slender strut the load in it will increase as the external load is increased until its magnitude reaches the Euler critical value : any further increase in external loading will cause slight bowing of such a member and its load will remain constant at the critical value. In the case of an initially tensioned wire the member behaves as a strut until the induced compression just balances the initial tension : it then ceases to function and is no longer an integral part of the framework.

A framework containing such members presents difficult problems, since all members are operative under small external loads and the structure may exhibit a high degree of redundancy : under large external loads it may reduce to a simply stiff frame, while intermediate loads may produce any degree of redundancy between these extremes.

For practical stress analysis purposes it is generally sufficient to take account of the two extreme cases, but in the case of a structure having a considerable number of members the work involved even in this is prohibitive. Such a position arises in the design of the hull of a rigid airship. Approximate methods of stress analysis have been given by the Airship Stressing Panel* for the case of a redundant braced tube. This analysis is legitimate for normal flight conditions of loading, but under exceptional loads some or all of the counterbracing panel wires resisting compression may become inoperative. It is essential that the stresses in the frame under the extreme loading conditions shall be known and the present work was carried out to check the accuracy of a suggested method† by which such stresses can be simply deduced from a knowledge of the stresses in the various members of the framework in its normal fully redundant state. To apply this method it is first necessary to calculate the loads in all members of the framework under the extreme conditions, assuming it to be fully redundant and all members capable of resisting compression of any required amount. In the case of a tubular braced frame this is readily done by the methods previously mentioned. The loads thus obtained will be found in some cases to exceed the initial tensions in the wires or the Euler critical loads of the struts, indicating in the first case that the wire is completely inoperative and in the second case that the strut is only exerting the critical load.

In order to obtain such conditions, external forces are imagined to be applied to the joints connected by these members of such a magnitude as to reduce the hypothetical stresses in them to the actual values.

For example, let Fig. 8 (*a*) represent a panel of a counterbraced framework and let the tension and compression in the diagonal members be T and C respectively calculated upon the assumption that the member EB is always operative.

Suppose in the first place that EB is an initially tensioned wire and that C is greater than the amount of the initial load : this member will then be completely inoperative.

This condition can be reproduced by superposing on the panel, reversed loads P at E and B as shown in Fig. 8 (*b*) where P is made equal to C.

The tension in AD will then be $(T + T_o)$ where T_o is the tension due to the

* R. & M. 800. Report of the Airship Stressing Panel.
† Due to Mr. R. V. Southwell, F.R.S.

forces P and the load in EB will be (C – P), *i.e.*, zero as required. The loads in AB, etc., are similarly found by adding algebraically those calculated on the original assumption and those obtained by the application of the forces P at E and B.

If EB, instead of being an initially tensioned wire, were a strut with an Euler critical load Q, the final load in EB would be Q, and P would be made equal to (C – Q) instead of C.

If this superposition were made for each panel in a framework and the complete structure analysed under such superimposed loads, an exact solution of the problem would be obtained but the work would be heavy. It was therefore suggested that each panel should be treated as if it were an independent frame, *i.e.*, the effects of the superposed loads P should be assumed to be confined to the panel ABDE, etc.

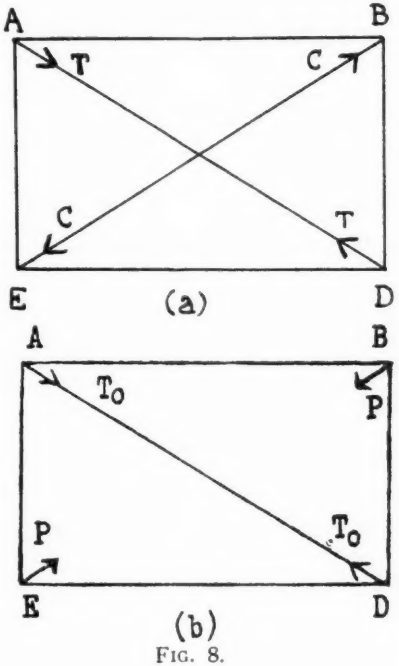

FIG. 8.

If this is done the work is very easy, but it is of course an assumption that requires check to determine the degree of approximation involved.

Such a check was made as follows:—One of the experiments previously described consisted in measuring the loads in the members of the framework fitted with a $\frac{7}{8}$in. solid steel keel member, the end bulkhead being fitted with 4B.A. radial bracing members.

The measured loads taken from this experiment were used as a basis for obtaining an estimate of the loads when all counterbracing wires became inoperative, in the way just described.

The counterbracing wires were then actually slackened off and the actual loads in the remaining tension members were measured experimentally.

Table XIX. gives the comparison between the calculated loads and the actual loads. The figures of the earlier experiment mentioned above were reduced to correspond to an external force of 100 lbs. at joint D_4, since it was desirable not to exceed this load on the framework in its nearly simply braced condition.

TABLE XIX.

Member.	Measured Load.	Load from Table II.	Error per cent.
A_1B_1	77·0	72·7	−5·6
B_1C_1	39·2	35·3	−10·0
C_1D_1	0	0	0
A_2B_2	19·9	21·0	+5·5
B_2C_2	−0·5	1·7	
C_2D_2	−19·6	−17·6	−10·2
A_3B_3	−66·2	−61·8	−6·6
B_3C_3	−52·0	−49·6	−4·6
C_3D_3	−38·0	−38·1	+0·3
A_4B_4	−147·2	−156·1	+6·0
B_4C_4	−97·6	−104·4	+7·0
C_4D_4	−51·0	−52·3	+2·6
A_1B_2	25·0	23·8	−4·8
B_1C_2	24·6	24·3	−1·2
C_1D_2	25·5	22·9	−10·2
A_2B_3	49·6	49·7	+0·2
B_2C_3	51·4	48·9	−4·9
C_2D_3	49·4	49·5	+0·2
A_3B_4	32·2	33·6	+4·3
B_3C_4	30·3	33·9	+11·9
C_3D_4	33·2	34·0	+2·4

In this experiment the loads in the wires only were measured and the tabulated values are the mean of the two sides of the structure. From these measured values the loads in the longitudinal members were obtained by resolution at the joints.

The general agreement is good and it would appear that the method described is sufficiently reliable to give a good indication of the stresses in the extreme condition when redundant members have ceased to operate.

The cases taken for this investigation were as drastic as possible, the whole of the counterbracing wires being disconnected. It is improbable that any one condition of loading would cause this to occur in an actual structure, and in that case the errors would almost certainly be less in magnitude than those tabulated.

The experimental work is still in progress, a structure being now under investigation in which the longitudinal members are continuous instead of being pin-jointed at the transverse frames. At the time of writing this paper the experiments were insufficiently advanced to allow of any results being given, but these may perhaps be communicated to the Society at a later date.

In concluding, I must pay a special tribute to the work of my assistants in this research—Mr. J. F. Baker, B.A., who joined me at the beginning of operations and stayed for the year during which the earlier experiments were conducted, and Mr. G. H. W. Clifford, M.Sc., who succeeded Mr. Baker on the latter's appointment to the Airship Design staff at Cardington. Without their steady and enthusiastic work the research could not have been carried out.

Further, my thanks are due to the Aeronautical Research Committee for financing the work and for giving me permission to communicate the results to this Society.

Discussion

Mr. R. V. Southwell said: I should like to begin my remarks by expressing my very real gratitude to Professor Sutton Pippard for the excellent lecture he has given us, and especially for the way in which he has explained the paper to-night, which has made it so much more clear to us than a mere reading could have done. But time is short, and that is my reason for passing on at once to matters of controversy.

There are two points in particular which I should like to mention. The first is perhaps a mere matter of wording. Professor Pippard seems to imply that by applying to *all* the panels of his structure what at Cardington we call the "device of the separate panel," a specially hard test of that device has been imposed—in fact, a harder test than need be expected in practice. I am inclined to differ from that view; I think that the method of the separate panel will work better and better the more extensively it is employed.

This sounds rather strange, but suppose that one had an exact solution for a thoroughly redundant structure, and applied the method to one panel only. Clearly, one would not get an exact result. Yet if the redundancy of that structure consisted entirely in the number of members being more than was required for stiffness, then if one applied the method to each panel in turn—one at a time, but finally to every one of them—in the result one would get, as the final system of stresses, a system of stresses which satisfies the conditions of equilibrium at *every* joint, and so must be the one possible solution, because the framework has by now been reduced to a simple frame, in regard to which there is no ambiguity. I think that our hopes of this "method of the separate panel" are based rather on the consideration, that an enormous number of the redundancies in any airship will effectively have disappeared by the time that the loads have attained such magnitudes that they are likely to cause actual failure of the structure.

I turn now to the difficulty described by Professor Pippard in regard to the action of the pyramidal nose-piece in his model. These very stout members did in fact bow under the loads which were incurred by them in constraining the cross sections to remain plane, and he deduces from this fact that the members must indeed be stout if they are to keep plane sections plane in actual practice. I do not see my way very clearly here; but one may say fairly definitely that unless the base of the pyramidal head is so rigidly braced in its own plane that it is effectively prevented from distorting in that plane, an increase in the size of the converging members of the pyramid will do more harm than good, because distortion of the shape of the base must, with rigid converging members, be accompanied by distortion of the base out of its plane. For this reason, I quite agree with the main conclusion of the Lecturer, that the main problem in bracing the pyramidal head is to supply sufficient stiffness against distortion in its own plane rather than against distortion out of its plane.

I think we are very fortunate in being able to hear about these methods to-night, and even more fortunate in the fact that Professor Pippard is able and willing to devote himself to these airship problems. It may be asked, are we testing experimental methods by theory, or theory by experiment? Irish as it may sound, I am inclined to say that we are doing both. These experiments give a feeling of confidence that was not present before—a confidence that the methods of stressing which we are trying to devise are being pursued along right lines. But we have not reached our goal yet, and I venture to express the hope that these experimental methods, now proved to be adequate for the measurement of stresses, will be applied to structures more representative of the new airships, as soon as these have taken definite form. What is needed most in airship research is continuity. How much damage was done by the decision,

after the R.38 disaster, to stop all research on airships, only those who are facing the problems of the new designs can say. This Society can fairly take pride in having contributed to bring about a better state of things, and I hope that it will continue to press for continuity in research on airship problems.

Miss H. P. HUDSON: I think the general agreement in theory and practice is most refreshing and encouraging.

I should like to know more about the panel method for the slackening of wires. The loads in Table XIX. are small so that an error of 1lb. may realise large percentages. Would it be at all possible, if a more accurate method were required, to extend that method to the immediately adjoining panels, stressing three or five, or would it imply prohibitive labour?

Colonel RICHMOND: The excellent work done by Professor Pippard and his colleagues on the airship stressing panel has been invaluable in laying the foundation on which to build up in this country a sound technique for the stressing of airships, and is on a parallel with the similar invaluable work he carried out in connection with aeroplane stressing during the war.

I think our warmest thanks are due to him for the concise summary he has given us of the Airship Stressing Panel's work, and for his splendid account of the extensive experimental work he has carried out to check the validity of the methods laid down by that panel.

Certain recommendations made by the Airship Stressing Panel require us to depart pretty radically from the accepted German design of rigid airship, in order to make the methods laid down by the Panel as valid as possible; one may quote, for example, the effect on the distribution of stresses caused by lack of symmetry such as is introduced by the longitudinal keel.

Except for some early rigid airships designed by the Admiralty, some of which did in fact omit the longitudinal keel, the whole of rigid airship construction throughout the world to date, may be said to have been an almost Chinese copy of German practice. In consequence, it is only as we progress with designs which are radically different from these, and which are perhaps more amenable to the treatment suggested by the Airship Stressing Panel, that we shall reap the full benefit of the Panel's work, or that we shall discover in what way it is incomplete or requires modifying.

The Zeppelin type of airship differs radically from the type of structure postulated by the Airship Stressing Panel in a good many respects. For example, it is far from pin-jointed, and the amount of offsetting between various members which occurs at the joints is very considerable. Professor Pippard's experimental work has, however, demonstrated very clearly two difficulties which may well arise in connection with any type of hull design. These are the effect of the initial tensioning of bracing wires, and the manner in which the strict application of St. Venant's principle depends on the stiffness of the bulkheads.

With regard to the former, I should like to say that from a practical point of view it is extremely difficult with the Zeppelin type of construction to ensure that any specific amount of initial tension can be put in all the bracing wires simultaneously. Further, from practical experience I should be inclined to differ from Professor Pippard when he says towards the end of his paper that "this analysis is legitimate for normal flight conditions of loading," meaning, I take it, that there is sufficient initial tension for all bracing wires to be operative under such normal conditions. With the amount of initial tension which it has been found practically possible to use, this is not the case. Moreover, with the Zeppelin type of construction, this initial tension is reduced in the process of time, presumably owing to the flattening of wire loops, the bending of wiring plates, and development of general slackness in the joints.

From a theoretical point of view, I do not think that sufficient emphasis has

been laid on the fact that the structure must be stressed for the self-straining introduced by the initial tensioning of the bracing wires.

It will be obvious that it is not only impossible, but also undesirable to put that amount of self-strain in the bracing wires which would prevent any of them going slack even under normal conditions of flight, especially if one is designing for the normal loads multiplied by their factors of safety.

This question does in fact constitute a real bugbear, and some further consideration is necessary in order to determine the best method of dealing with it.

The second question of the application of St. Venant's principle is equally difficult, as it does not appear theoretically possible to lay down any general rules for simply determining what must be the magnitude of the elastic properties of the bulkhead in relation to the rest of the structure, in order for the principle to apply with a tolerable degree of accuracy, and it will be realised that Professor Pippard's model structure is not sufficiently closely related to the actual structure of an airship for his experimental results to be used quantitatively.

With the object of gaining further light on this point we have been endeavouring to repeat very similar experiments to his on a portion of an actual airship hull.

It would perhaps not be out of place if I gave a brief description of the apparatus employed and the general nature of these experiments.

Two inductance coils with iron armatures in series are used. The current flowing is proportional to the airgap if the voltage is proportional to the frequency.

There are three methods of measuring, Jenkin's, the ammeter, and the oscillograph.

The Jenkin instrument measures one to two hundredths of a millimetre in a total strain of 1 mm., which represents about one-fifth of the yield strain for steel or duralumin, and therefore the range of accuracy is .2 to 2 per cent.

The ammeter can be read to .05 mm. and is therefore much more accurate, but suffers from other disadvantages.

The order of accuracy of the oscillograph is about the the same as that of the Jenkin instrument.

The additional errors which may occur with any of the methods are an error of about .1 per cent. on reading the gauge length, and a variability amongst the various gauges of 1 per cent. This could, however, be got over by calibrating all the gauges in a micrometer measuring machine.

The oscillograph apparatus was specially designed to measure the strains in a large number of members within a very short period of time, in order to obtain some direct reading of stresses on airship members, when flying in weather conditions which are too disturbed to be amenable to theoretical calculation. As a matter of fact, with a commutator arrangement it is possible to put forty different gauges into the circuit in turn and obtain records from each one within a space of about four seconds.

An opportunity has not yet occurred of using the instrument in actual flight, but owing to the rapidity with which records can be taken it is proving very useful in some experiments which are now being carried out in our attempts to repeat Professor Pippard's work on a portion of an actual airship hull.

The only satisfactory fixing which could be made for the portion of the hull was of course the ground. It was desirable to have at least three complete bays of the airship in order to test the St. Venant's principle, and the airship R.80 was chosen for this purpose as being the only one of which three bays could be accommodated within the shed. The topmost bulkhead is loaded laterally by ropes which pass over pulleys in the roof and carry trays on which the weights are placed.

The experiments have not yet proceeded far enough for any actual results to bequoted, but the matter has gone far enough to show what difficulties arise owing to the yielding of wire loops and lugs, etc., and from the uncertainty as to the degree of initial tension.

We have been fortunate in this work in having the assistance of Mr. Baker, who actually assisted Professor Pippard in his experiments, and to whom I think very great credit is due.

Mr. WYN EVANS: As one of the old airships' staff, who was responsible for the construction of the hulls of some six of the old rigid airships, I should like to make one or two very general remarks. We no doubt realise now the extremely valuable work that Professor Pippard and Mr. Southwell have done for us. With reference to R.38, I think we should realise that at that time we had a very big problem set us in outflying the Germans in speed and attainment of height, and the work had to be done in double quick time. We had to follow recognised practice and recognised methods of calculation. How near we were to success was shown by the successful trials prior to the terrible disaster, but how far from it by the disaster itself. To attain extreme altitude involved an extremely small factor of safety, and it was recognised that we were working to that extremely small factor of safety.

I can endorse Colonel Richmond's remarks regarding the great difficulty in attaining the necessary tensions in the tension members during the actual construction of these rigids.

I should like to thank Professor Pippard for his extremely valuable paper which will be a notable addition to the records of the Society.

Mr. J. F. BAKER: There is one point I should like to raise relating to the principle of St. Venant.

The results of loadings Nos. 6 and 7 without bulkhead wiring make me wish that Professor Pippard had done a similar case, but with the loads applied in the direction of the longitudinals.

Radial bracing in the end bulkhead immediately distributes a system of loads applied in the plane of that bulkhead, while as in (6) and (7) when the radial bracing is absent, no such distribution takes place. It seems possible, therefore, that were a load system applied in the direction of the longitudinals no distribution would occur, even though the end bulkhead was radially braced.

It is possible to analyse the structure for a longitudinal load system, of zero axial load and zero moment, by similar methods to those used by Miss Chitty, but the equations are so cumbersome that a solution in general terms is unwieldy. On substituting values for a special case, the loads in the members are obtained in terms of the applied loads, and it is possible so to chose the applied system that the loads in certain of the members increase from the free end.

I hope Professor Pippard will find the opportunity to put these calculations to an experimental test.

Dr. B. C. LAWS: When I received from the Secretary an announcement of Professor Pippard's paper I had no intention of taking part in the discussion, but as the Chairman has kindly invited me to say something on the subject of the paper, I gladly comply, although I have not had the opportunity of doing more than taking a superficial view of the paper.

I will at once say that I think the paper is one of great value to aeronautical students and will, I believe, form a valuable addition to the Proceedings of this important Society.

It represents much patience and concentration, and the Author and those who have worked with him in this investigation are deserving of all praise.

For myself, I view the paper from without, as I am not intimately associated with the interesting and fascinating work of aeronautics, although taking a keen interest in the study. I am not sure whether the results obtained from experiments of this kind may be taken literally as representative of what might possibly happen in an airship in being. It seems to me that the assumptions made on the basis of the experiments may not, except under very special conditions, be reproduced in an airship in flight, but this will not detract in any way from the value of the experiments which should form a substantial groundwork from which to make deductions.

The first point to which I will refer pertains to the apparatus employed and relates to the measurement of strains in the members of the framework and the method adopted in fixing the framework itself.

Some few years ago I carried out an inquiry into the distribution of stress in rectangular mild steel plates under certain conditions of loading and fixing of the plates, which necessitated the measurement of very small deflexions. It was found to be necessary to employ a means of measuring other than the extensometer usually employed in determining strains. The apparatus adopted was practically identical with that used by the Author, and is set out in the Proceedings of the Institution of Civil Engineers, Vol. CCXIII., where a full account of the experiments and analysis is given.

As the deflexions were small it was absolutely necessary that the whole apparatus should be free from vibration of any kind so that the results would not be vitiated. The apparatus was supported on a brick foundation built upon a solid concrete floor.

Now it seems to me that it might have been better had the Author's framework been attached to such a foundation rather than to a wall which, apart from the rag-felt attachment, must be liable, more or less, to movement or vibration, considering which the general closeness of the calculated to the experimental stresses, etc., is surprising and indicates with what great care the experiments were conducted.

The ball and plug joints adopted by the Author for the members are very neat, but I do not think it can even approximately be assumed that they constitute pin joints except for the bracing members. The very precaution taken to make the connecting plugs in the principal members so short as to render them free from buckling seems of itself to destroy the idea of a pin joint by making the attachment rigid.

I am therefore inclined to think that if the calculated figures are based on an assumption of pin joints they cannot represent the real results for the principal members as the bending moment resistance is certainly experienced at these positions. This seems to be reflected in the percentage differences recorded in the paper relating to these members, and in view of what the Author says at the end of the paper that "further experiments are in progress in which the longitudinal members are continuous," I venture to think that the results, when obtained, will relatively be pretty much the same as those referred to in this paper.

The mode of attaching the plugs to the tube ends by soldering seems undesirable and objectionable. This seems to be borne out by the statement that the joints gave out under the low factor of safety *two* for the member, and that the soldering generally was found to be variable in efficiency. I think perhaps in practice the plugs could be more effectively pinned to the members, either by drifting or screwing.

But the factor *two* is really startling and represents a margin of safety which in the principal constructive member of vessels sailing the seas would never be considered.

Further, the experimental conditions were static, and it is not an exaggeration to say that this factor might be so reduced as to approach unity (*i.e.*, no margin of safety at all) under dynamic conditions in the case of an airship in flight.

In the paper it is stated that the plug or dowel itself gave out under a test load of about eight per cent. greater than the load strength of the soldering. Relatively this is quite reasonable as there is no necessity for making the strength of this part (the dowel) greater than the attachment itself (the soldering).

I do not agree with the Author when he says that the *initial tensions*, in what is designated the strut members, is *immaterial*. That initial tensions must exist or be present in all or most of the members is undisputed, but surely the amount of tension is not only a matter of concern to the designer and navigator alike, but is a factor upon which the wellbeing or ultimate constructive efficiency of the ship will depend. To reduce such stresses to the necessary minimum by good designing and good workmanship is the aim of the designer, and it is probable if a particular member has to be normally so stressed in tension that under other conditions it assumes the function of a strut, the *real factor of safety* of the ship might be very considerably diminished, *e.g.*, if we started with a safety factor of *two* we might find that there is little or no margin of safety left under certain changed and not very severe conditions of load.

I would be glad if the Author will explain how it is possible to determine—as is stated in the paper—when the initial tensions are sufficient. It seems to me that the only criterion is experience, which in the case of an airship might be misleading.

With regard to the transverse bulkheads, I quite agree that it is necessary to preserve the form of these bulkheads, but it is not clear—as is assumed in the calculations—that they may be free to move out of their plane without effect. Within certain narrow limits of movement this might be taken as approximately correct, but if the bulkheads come to suffer more than a certain amount of distortion (planar), the members of the bulkheads would experience stress not only due to bending, but torsional stresses which might be prejudicial to the efficiency of the structure.

What would have added to the value of the paper is to have included the theoretical principles upon which the calculations have been based; in the absence of these one is deprived of the opportunity of making calculations for oneself, by way of comparison. If the Author can find time to include even an outline, I am sure it would enhance the value of the paper which, as it stands already, will be of much value and interest to those who have the development and wellbeing of aircraft at heart.

Mr. W. L. Cowley: It has been most enjoyable to hear Professor Pippard's lecture. The problems that the Airship Panel had to face were very difficult, but they have given us a very useful weapon in the St. Venant principle treated by the Lecturer.

Professor Pippard is rather pessimistic about some of his figures. I feel sure that even errors of 20 per cent. are not large considering the difficulties of the problem. After all, designers use factors of safety of 4 or even 8 to cover errors such as those shown by Professor Pippard, and they would count themselves fortunate if they could rely on an accuracy of the order of that obtained by the Lecturer.

This work on models has brought to my mind some work which I did with Professor Levy some five or six years ago. We suggested in a paper in *Engineering* that tests should be carried out on model structures to determine the stresses in complicated aeroplane structures; we mapped out a scheme whereby

we could calculate by means of the dimensional theory the crippling or buckling load on a structure from that found on a model structure.

I should like to ask Professor Pippard if he thinks there is any possibility of using that work for airship problems. An airship structure is an extremely complicated structure, and probably the model would be very difficult to make, but it seems to be a useful method of testing.

Reply

I should like to express my appreciation of the way in which my paper has been received by the Society. From its nature it was a difficult subject to talk about, both from my point of view and from that of those who have contributed to the discussion, and I am specially pleased therefore that so many have entered into that discussion.

Mr. Southwell has raised two interesting points. The first one dealing with the accuracy of the "device of the single panel," has presented the question in a rather different light to that from which I had viewed it, and I am inclined to agree with Mr. Southwell's contention. My reference to the drastic nature of the experimental case taken did not, however, have quite the meaning that Mr. Southwell has suggested although I am afraid that I worded it rather badly. I had in mind that probably only a limited number of wires would slacken off in any one extreme flight condition, and that the main calculations for strength would only need modification in localised areas. In view of other speakers' remarks, however, it appears likely that all counter-wires will become slack even in normal flight, and in this case I agree with Mr. Southwell's view. I also agree with his remarks on the effect of the pyramidal nose-piece. It is undoubtedly of great importance that the base of the pyramid should be braced as rigidly as possible in its own plane.

Since the paper was read it has been decided to stop the experimental work for the present at any rate, but I hope that it will be recommenced later as Mr. Southwell suggests on a structure more typical of modern developments in airship design.

In reply to Miss Hudson I would say that in general resultant errors were not expressed as percentages, partly for the reason that she puts forward and partly, indeed principally, because the errors are really in the nature of a constant amount due to the limitations of the method of strain measurement. They are not dependent upon the actual strain, and I should anticipate the same possible error (of $\pm$ 1lb. on a wire member), whether the load in the member was 10lbs or 100lbs. In the one case the error would be 10 per cent. and in the other only 1 per cent. This method of expressing results was consequently avoided whenever possible.

From a practical point of view, I think that any extension of the separate panel method as suggested by Miss Hudson would involve a prohibitive amount of work with very little, if any compensating value.

I must thank Lieut.-Colonel Richmond for supplementing my paper with the very interesting slides and description of the full-scale work now in progress at the Royal Airship Works. I appreciate Colonel Richmond's remarks on the subject of initial tensioning and I can readily imagine the difficulties in an actual ship, but I am rather surprised to hear that it is considered doubtful whether the wires would function as struts even under normal conditions of steady flight. If this is really the case, I can only suggest that it is useless to take them into account at all when analysing the stresses in the structure and we can reduce our redundancies very considerably.

Naturally I agree with Colonel Richmond that the structure must be "stressed" for the loads, due to initial tensioning. These loads are additive to

those arising from flight loads and may be of some considerable importance. My reference to their lack of importance was merely in regard to the work on the model, where we were concerned in finding the stresses in the members due to a known increment of external loading and not the actual final values. If it were at all possible, from the standpoint of weight, I should be strongly in favour of replacing initially tensioned wire diagonal members by light struts, with end attachments so designed as to take tension loads. Such a method would eliminate the uncertainty of initial stresses. I am afraid, however, that this solution is scarcely practicable.

I shall await with considerable interest a description and detailed report of the full-scale strain measurements outlined by Colonel Richmond, and I shall be especially interested to see how strain measurements on a built-up member are translated into loads; in the model structure, of course, direct calibration in a testing machine was a simple matter, but the problem would appear considerably more difficult in the case of full-scale work.

Mr. Cowley has mentioned a suggestion made by himself and Professor Levy in reference to the use of models in aeroplane structural analysis. If I recollect rightly, I discussed this with them once when we all met at Farnborough. I do not remember what I thought about the project then, but I am quite convinced now that their suggestion was a good one. I am sure that a great deal of valuable help could be gained by the use of structural models, not perhaps to obtain actual stresses in a given aeroplane, but to assist in the development of theory. I would like to see the method I have described to-night used on a full-sized aeroplane during destruction tests. The loads in the wires could be obtained and most valuable confirmation or otherwise of existing theory would be produced.

I am in sympathy with Mr. Wyn Evans' remarks as to the difficulty of the problem set to the designers of R.38. Those of us who were on the Committee which investigated the disaster to that ship, realised the extreme nature of the demands for performance and that sacrifices were necessary to obtain it.

I am very pleased that Mr. Baker was able to be present to-night and to take part in the discussion. Mr. Baker was with me from the initiation of the work and we shared the difficulties of design, both of instrument and structure. Those difficulties were considerable, and Mr. Baker's hard work and enthusiasm contributed largely to any success which has attended the research.

I have not had a chance yet to go into his calculations on the effect of longitudinal loads on the hexagonal frame; the results he has obtained are certainly startling and need careful investigation. I hope to go carefully into this matter with him as it involves a very important general principle. It should also be possible to arrange an experimental check on his result as he suggests and this I hope to do later.

In reply to Dr. B. C. Laws, I would say that the experimental work had as a primary object the testing of certain hypotheses upon which comparatively simple design methods had been produced. The full account of such methods is given in the Report of the Airship Stressing Panel (R. & M. 800), and if Dr. Laws will examine that document he will appreciate that his suggestion that I should incorporate theoretical principles in the present paper is not quite a practicable proposition; it would add enormously to the length and would probably swamp the main subject of the paper.

I am very interested in Dr. Laws' reference to his own apparatus. I had not seen this when we designed our own, but I shall take an opportunity of studying his design.

Fortunately, we found very little trouble due to vibration other than in exceptional cases. Normally the instrument and structure were quite steady, and

abnormally heavy traffic, high winds and certain plant running were the only disturbing features.

I do not agree with Dr. Laws' remarks as to the efficacy of the pin joint approximation. The dowels had a value of *EI* of about 1 per cent. of that for the tubes, so that the resistance to bending they offered was almost negligible. This was proved experimentally when a dowelled strut gave the same collapsing load as a ball-ended member, both being very near the Euler critical load; in actual fact the dowel-ended strut was nearer to the Euler critical than the other.

Dr. Laws' forecast of the results of the work on a model with continuous longitudinal members is very accurate, as will be seen from the addendum to my paper, in which those later results are given. I venture to think, however, that the basis of his prediction is not quite the correct reason for the agreement in results shown to exist. Dr. Laws is under a misapprehension as to the constructural details; of course, the methods I used on the model bear no relation whatever to actual airship design and my figures refer to the model only. The soldering was used as I did not wish to drill the ends of the tubes, and although some trouble was experienced this was not at all serious. The factor of safety in an actual ship would obviously have to be much more than the figure I gave as that on the model.

Another point in which Dr. Laws and I are at cross purposes is in regard to the importance of initial tension loads. The theoretical results I was examining gave the *increase* in stress due to the application of an external load system and I was only concerned in verifying these results. In design work, of course, the initial or self-straining stresses must be added to these increments due to external loads.

The method we used to determine the sufficiency of initial tension was simple. The structure was trued up and the wires tensioned. The load was then applied to determine whether all members were still taut. If they were, the experimental strain measurement was carried out; if not, additional tensions were given to the wires. This, again, has no reference to the procedure in an actual airship; in that case the problem is a difficult one, as other speakers have indicated.

The question of the distortion of bulkheads is dealt with in R. & M. 800 and Dr. Laws will appreciate the position if he consults that paper.

I must thank Dr. Laws for his interesting contribution to the discussion and I hope I have cleared up the points he finds troublesome.

The Secretary,
The Royal Aeronautical Society,
7, Albemarle Street, W.1.

Dear Sir,—We beg to acknowledge your courtesy in forwarding to us an advance copy of Professor Pippard's paper on airship structures.

We should like to say how extremely interesting we find Professor Pippard's paper, and to congratulate him on the great care and ingenuity with which he has carried out these experiments.

At a first reading we have been greatly impressed by the agreement of Professor Pippard's final conclusions with the initial assumptions made by the writer and his colleagues when in 1913 work was started on the design of the series of airships built by Messrs. Vickers, Limited, which culminated in the R.80.

In our own case, our conclusions were arrived at as the result of the analysis of redundantly braced space frames of a relatively simple character, carried out

by methods generally involving successive approximation. Later we were able to corroborate our ideas by carrying out tests on the full-size structures when finally erected before and after inflation. Obviously, however, we had to confine our attention to the measurement of the forces set up in the wiring of the ship, noting the changes produced by modifications in the loading applied, and afterwards to estimate the forces in the girders from equilibrium considerations.

Generally speaking, we obtained ample verification, at the time, of our methods by such experiments and were able to eliminate unnecessary structural weight in our later ships with a considerable degree of confidence as well as to take full advantage of Zeppelin experience in analysing the structures of captured ships. I may say that in no case did we ever have any structural failure under working conditions.

It will be well understood, therefore, that Professor Pippard's work is of extraordinary interest to us and we hope to make the fullest possible use of it.

The outstanding item of technical interest in the results is, I venture to think, that they accentuate the importance of what Professor Pippard refers to as the secondary stresses; the effect of the local forces set up in the structure due to the application of concentrated loads represented in the full size ship by the attachment of power units, passenger quarters, etc., at particular points of the structure.

We regret that Commander Burney is at present abroad, as I am sure he would have wished to congratulate Professor Pippard personally on his valuable work and he will no doubt do so at a later date.

Yours faithfully,

For AIRSHIP GUARANTEE COMPANY, LIMITED,

J. G. TEMPLE (Lieut.-Col.), *Engineer.*

FURTHER EXPERIMENTS

BY PROFESSOR A. J. SUTTON PIPPARD, M.B.E., D.SC., F.R.AE.S.

Since the foregoing paper was communicated to the Society the Author, with the assistance of Mr. Clifford, has carried out a further set of experiments, and in order that the record in the Journal may be as complete as possible it was thought advisable to add a description of these. The experiments now to be described were carried out on a framework in which the longitudinal members, instead of being pinned at the joints, were continuous. The transverse frame struts were pinned to these as in the first structure. The object of this later work was to determine the extent to which the continuity of the longitudinals affected the stress distribution. Since the effect of continuity is to increase the redundancy of the framework to a considerable extent the theoretical analysis for this case becomes very complex, and so far no solution for the stress distribution corresponding to that available for the pin-jointed frame has been obtained.

Description of Structure

The general arrangement of the new structure and a detail of the joint are given in Fig. 9.

The leading dimensions of the frame were the same as in the first structure previously described; the side of the hexagon was 25in. and the length of each of the three bays was 30in. The six longitudinal members were attached to the same wall plates used throughout the earlier work and these attachments were made by dowels to give approximate pin ends. These longitudinals, continuous from the wall to the bulkhead D at which load was applied were $\frac{7}{8}$in.

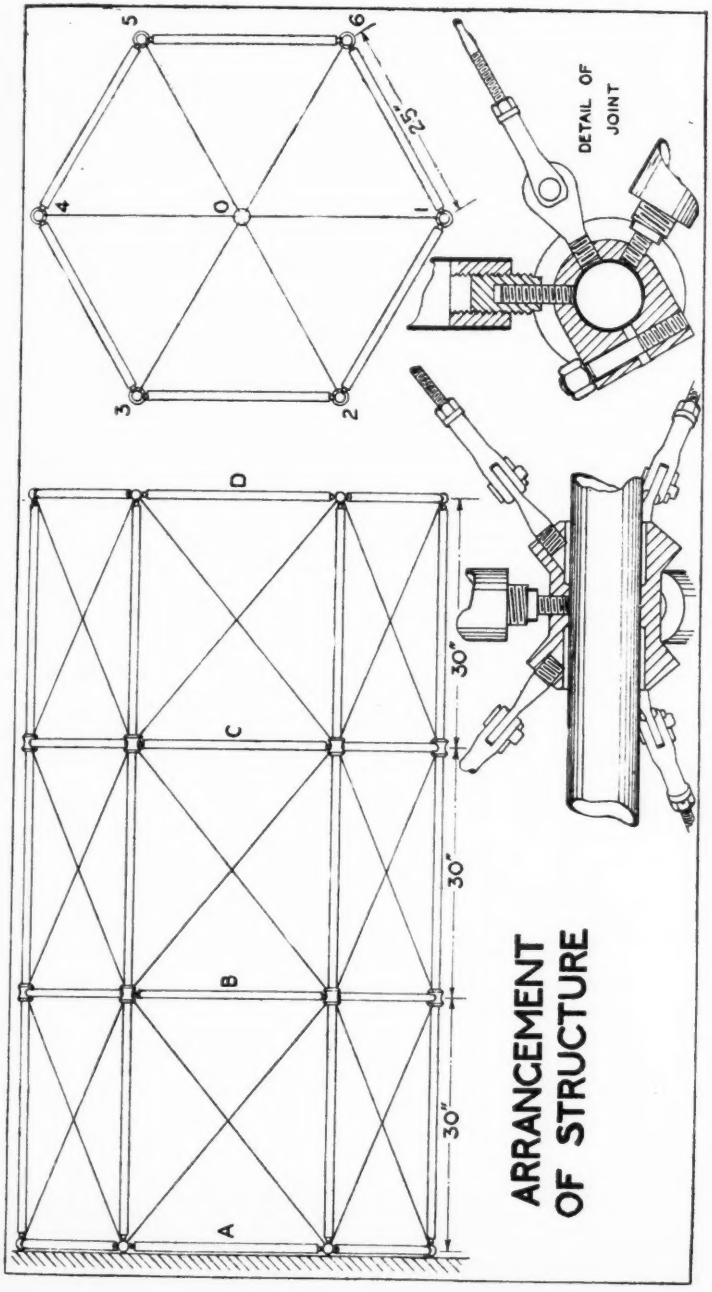
ARRANGEMENT
OF STRUCTURE
A
B
C
D
30"
30"
30"
0
1
2
3
4
5
6
.52"
DETAIL OF
JOINT

FIG. 9.

O.D. × 22 g. steel tubes specially selected for straightness. The top or keel member was replaced in certain experiments by a solid steel bar $\frac{3}{8}$in. diameter. All transverse frame struts were $\frac{3}{8}$in O.D. × 22 g. steel tubes and all bracing wires were 4 B.A. swaged rods.

The fittings for the attachment of the transverse struts and bracing wires to the longitudinals were turned from solid steel bar. Essentially the fitting consists of a split collar with lugs carrying a screw for tightening it up. This collar is made with such clearance as to give an easy sliding fit over the longitudinal member, the width of the bearing surface being $\frac{1}{4}$in. When the collar is tightened by the screw the friction grip is sufficient to locate it satisfactorily at any point on the longitudinal member. Farces were turned on the outside of the collar at the correct angle to allow for taking off the bracing wires. The collar was tapped to receive the dowels to which the transverse struts were attached and also for the wiring lugs.

All other details of the framework were as in the previous structure.

Owing to the alteration in the joint from the earlier one the lengths of bracing wires were different and new 4 B.A. rods had, therefore, to be obtained. These, as delivered, were rather over the standard diameter and a new calibration of load against extension was thereby rendered necessary. This calibration showed that one division of the micrometer head corresponded to a load in the wire of 1.07$\frac{5}{8}$lbs. instead of 1.02lbs. as in the previous consignment of rods. These wires were uniform in size and no difficulty was experienced with them other than the initial one of calibration.

Checks on Experimental Results

In the earlier experiments three checks were available upon the accuracy of experimental results, viz. :—

(1) Agreement between forces in corresponding members under a symmetrical load system.

(2) Static equilibrium of all forces meeting at a point.

(3) Summation of vertical components of forces across any section to give the resultant shear at that section.

In the present set of experiments the third of these is not valid since the continuity of the longitudinal members introduces bending moments which are accompanied by a redistribution of shearing force.

Since the structure is attached to the wall by pin joints, however, a check is available, as the bending moment exerted by the wall fixing must be equal to the applied bending moment. The horizontal force at each wall joint can be calculated from the experimental loads and the resultant couple was found in all cases to agree very closely with the applied moment.

Experiment 1

Keel member $\frac{3}{8}$in. O.D. × 22 g.
Bulkhead D radially braced with 4 B.A. rods.
Load of 400lbs. vertically at D_4.

In this experiment the wires only were measured and both sides agreed well. The loads in the longitudinal members were deduced from considerations of balance at the joints. These loads are given in Table XIX. together with the loads obtained from the corresponding case of the pin-jointed framework.

The differences between the two sets of results are given in lbs. Since the limit of experimental accuracy has been taken as ±1lb., as in the previous work, a discrepancy of 2lbs. between the readings on any wire member might be

accounted for by experimental errors. Such values are italicised and have been neglected in the column showing percentage variations.

Two members show a variation of more than 10 per cent., but this may be fictitious since the corrections which might be applicable, due to experimental errors, exercise considerable effect upon the percentages.

TABLE XIX.

Member.	Loads. Continuous members.	Loads. Pin-jointed members.	Variation of continuous values from pin-joint. Lbs.	Variation of continuous values from pin-joint. Per cent.
A_1B_2	75·7	69.9	+5.8	+8.3
A_2B_1	−26.8	−26.7	*+0.1*	—
A_2B_3	105.3	103.5	*+1.8*	—
A_3B_2	−102.9	−103.7	*−0.8*	—
A_3B_4	30.2	35·5	−5.3	−14.9
A_4B_3	−77·5	−75·5	*+2.0*	—
B_1C_2	57·5	61.8	−4.3	−7.0
B_2C_1	−38.2	−40.6	−2.4	−5.9
B_2C_3	105.8	103.0	+2.8	+2.7
B_3C_2	−103.0	−103.5	*−0.5*	—
B_3C_4	47.0	38.5	+8.5	+22.0
B_4C_3	−68.7	−70.5	*−1.8*	—
C_1D_2	53·4	50.0	+3.4	+6.8
C_2D_1	−40.8	−44.6	−3.8	−8.5
C_2D_3	97.8	102.3	−4.5	−4.4
C_3D_2	−104.2	−102.8	*+1.4*	—
C_3D_4	56.8	57·4	*−0.6*	—
C_4D_3	−58.4	−59.6	*−1.2*	—
A_1B_1	333·2	344·2	−11.0	−3.2
A_2B_2	191.0	191.0	0	0
A_3B_3	−159.8	−164.1	−4.3	−2.6
A_4B_4	−401.4	−403.0	−1.6	0.4
B_1C_1	203 8	208.1	−4.3	−2.0
B_2C_2	118.1	117.0	+1.1	+1.0
B_3C_3	−95·3	−92.6	+2.7	+2.9
B_4C_4	−249.4	−240.0	+9.4	+3.9
C_1D_1	62.8	68.6	−5.8	−8.5
C_2D_2	39.1	40.6	−11.5	−3.7
C_3D_3	−30.3	−32.8	−2.5	−8.0
C_4D_4	−87.3	−89.0	−1.7	−1.9

In order to show the least possible variations the differences between the pin joint case and the continuous case have been corrected where necessary by the maximum allowable amount, viz., ±2lbs. on each wire and Table XX. shows the percentage differences in the loads in the members, after such correction. The loads in longitudinal members have been recalculated from the adjusted wire loads. Out of eighteen wire members nine show loads agreeing within the limits of experimental error. Of the remainder only one shows a variation of more than 10 per cent. and six less than 5 per cent. The variation in loads in the longitudinal members only exceed 5 per cent. in one case. It is clear, therefore, that the effect of continuity in the longitudinals in this experiment is unimportant. Further evidence in support of this is furnished by the amount of shearing force taken by the wires. If the members were all pinned this would

be 400lbs. in each bay, but due to the continuity of the longitudinals there is a redistribution which was as follows:—

Bay.	Shearing Force taken by wires. Lbs.
AB	401.6
BC	403.2
CD	393.6

The departures from the pin joint values are so small that no serious redistribution of internal stresses would be expected.

TABLE XX.

Member.	Variation of continuous values from pin-joint. Lbs.	Per cent.
A_1B_2	+3.8	+5.4
A_2B_1	—	—
A_2B_3	—	—
A_3B_2	—	—
A_3B_4	−3.3	−9.3
A_4B_3	—	—
B_1C_2	−2.3	−3.7
B_2C_1	−0.4	−1.0
B_2C_3	+0.8	+0.8
B_3C_2	—	—
B_3C_4	+6.5	+17.0
B_4C_3	—	—
C_1D_2	+1.4	+2.8
C_2D_1	−1.8	−4.0
C_2D_3	−2.5	−2.4
C_3D_2	—	—
C_3D_4	—	—
C_4D_3	—	—
A_1B_1	−5.1	−1.5
A_2B_2	−1.9	−1.0
A_3B_3	−6.2	−3.8
A_4B_4	5.1	1.3
B_1C_1	−1.2	−0.6
B_2C_2	0.1	0.1
B_3C_3	−1.3	−1.4
B_4C_4	10.3	4.3
C_1D_1	−2.8	−4.2
C_2D_2	−1.0	−2.5
C_3D_3	−2.0	−6.1
C_4D_4	0.1	0.1

Experiment 2

Keel member ⅞in. solid steel.
Bulkhead D braced with 4 B.A. rods.
Load of 400lbs. at D_4.

This experiment was similar to the last, but a solid keel was substituted for the tubular member. The results are given in Table XXI., in the same form as for the previous experiments, and even without modification the greatest difference between loads in a wire member is only 7.2 per cent. One longitudinal gives a difference of 17.0 per cent., but this is on a very small load and is not important.

Table XXII. shows the variation in the loads when the correction of ±2lbs. to the differences is applied as before. Ten out of the eighteen wire loads agree within the limits of experimental accuracy and in no case does the difference in loads exceed 5 per cent. The error of 17 per cent. on the C_3D_3 longitudinal is reduced to 5 per cent. and this value is nowhere exceeded. Hence, with the solid keel member the differences between the loads in the two cases of continuous and pin-jointed longitudinals is even less marked than in the first experiment.

The shearing force taken by the wires in this experiment was as follows:—

Bay.	Shearing force in wires. Lbs.
AB	397·4
BC	408.8
CD	390·4

Here, again, the departure from the pin joint values are so small that no serious modification in the stress distribution would be anticipated.

TABLE XXI.

Member.	Loads. Continuous members.	Loads. Pin-jointed members.	Variations of continuous values from pin-joint. Lbs.	Variations of continuous values from pin-joint. Per cent.
A_1B_2	69.0	67.9	+1.1	—
A_2B_1	−29.0	−27.5	+1.5	—
A_2B_3	98.1	102.5	−4.1	−4.0
A_3B_2	−98.0	−96.4	+1.6	—
A_3B_4	56.2	60.1	−3.9	−6.5
A_4B_3	−74.0	−74.4	−0.4	—
B_1C_2	65.6	60.7	+4.3	+7.1
B_2C_1	−36.0	−36.7	−0.7	—
B_2C_3	105.1	98.5	+6.6	+6.7
B_3C_2	−94.0	−97.4	−3.4	−3.4
B_3C_4	65.0	63.1	+1.9	—
B_4C_3	−73.2	−72.7	+0.5	—
C_1D_2	45.9	49.5	−3.6	−7.2
C_2D_1	−42.7	−42.3	+0.4	—
C_2D_3	97.4	99.2	−1.8	—
C_3D_2	−99.3	−98.9	+0.4	—
C_3D_4	64.5	67.6	−3.1	−4.6
C_4D_3	−71.9	−68.4	+3.5	+5.1
A_1B_1	336.5	333.2	+3.3	1.0
A_2B_2	179.3	179.5	−0.2	—
A_3B_3	−111.0	−115.7	−4.7	−4.4
A_4B_4	−508.0	−510.0	−2.0	0.4
B_1C_1	191.7	197.6	−5.9	−3.0
B_2C_2	104.7	110.0	−5.3	−5.0
B_3C_3	−70.2	−67.7	+2.5	+3.7
B_4C_4	−309.5	−306.0	+3.5	+1.1
C_1D_1	65.7	65.1	+0.6	+1.0
C_2D_2	40.3	38.0	+2.3	+6.0
C_3D_3	−19.6	−23.7	−4.1	−17.0
C_4D_4	−99.2	−104.0	−4.8	−4.6

In order to determine whether a more rigid bulkhead bracing would affect the differences in loads between the two frameworks, experiment No. 1 was repeated with the D bulkhead braced with $\frac{5}{8}$ solid rods. The experimental values are given in Table XXIII. together with those obtained in the corresponding experiment on the first structure.

TABLE XXII.

Member.	Variation of continuous values from pin-joint. Lbs.	Per cent.
A_1B_2	—	—
A_2B_1	—	—
A_2B_3	−2.1	−2.0
A_3B_2	—	—
A_3B_4	−1.9	−3.2
A_4B_3	—	—
B_1C_2	+2.3	3.8
B_2C_1	—	—
B_2C_3	+4.6	4.7
B_3C_2	−1.4	−1.4
B_3C_4	—	—
B_4C_3	—	—
C_1D_2	−1.6	−3.2
C_2D_1	—	—
C_2D_3	—	—
C_3D_2	—	—
C_3D_4	−1.1	−1.6
C_4D_3	−1.5	+2.2
A_1B_1	1.1	0.3
A_2B_2	2.1	1.2
A_3B_3	0.4	0.4
A_4B_4	−2.5	−0.5
B_1C_1	−2.6	−1.3
B_2C_2	−1.5	−1.4
B_3C_3	3.3	4.9
B_4C_4	0.3	0.1
C_1D_1	nil	nil
C_2D_2	1.3	3.3
C_3D_3	−1.1	−5.0
C_4D_4	−1.7	−1.7

Experiment 3

Keel member $\frac{3}{8}$in. O.D. × 22 g. steel tube.
Bulkhead D radially braced with $\frac{1}{8}$in. steel rods.
Load of 400lbs. at D_4.

Compared with experiment No. 1 the percentage differences in the longitudinal members are larger, the maximum being 12.9 per cent.

In Table XXIV. the differences in loads are given after allowance has been made for the possible experimental errors. There is one large difference of 22.5, but this is upon a small load and apart from this the differences are small, only one of the remaining wires being over 5 per cent. None of the longitudinal members show errors of 10 per cent. and only three exceed 5 per cent. The results of this experiment, therefore, confirm the previous conclusions as do the figures for the shear force taken by the diagonal wires set out below.

Bay.	Shear force in wires. Lbs.
AB	401
BC	394
CD	398.6

TABLE XXIII.

Member.	Loads. Continuous members.	Loads. Pin-jointed members.	Variation of continuous values from pin-joint. Lbs.	Variation of continuous values from pin-joint. Per cent.
A_1B_2	72.8	68.4	+4.4	6.4
A_2B_1	−24.0	−27.1	−3.1	−11.4
A_2B_3	105.2	104.5	+0.7	—
A_3B_2	−104.0	−106.5	−2.5	−22.3
A_3B_4	35.7	27.5	8.2	29.8
A_4B_3	−74.8	−72.8	2.0	—
B_1C_2	64.0	63.2	0.8	—
B_2C_1	−37.3	−35.7	1.6	—
B_2C_3	104.5	107.6	−3.1	−2.9
B_3C_2	−100.2	−105.0	−4.8	−4.6
B_3C_4	38.5	36.7	+1.8	—
B_4C_3	−66.1	−63.5	+2.6	4.1
C_1D_2	55.8	53.1	2.7	5.1
C_2D_1	−49.5	−43.8	5.7	13.0
C_2D_3	100.9	105.0	−4.1	−3.9
C_3D_2	−105.4	−105.5	−0.1	—
C_3D_4	49.8	45.8	4.0	8.7
C_4D_3	−54.4	−52.0	2.4	4.6
A_1B_1	354.5	343.0	+11.5	3.3
A_2B_2	181.3	204.1	−22.8	−11.2
A_3B_3	−178.9	−197.4	−18.5	−9.4
A_4B_4	−376.0	347.0	29.0	8.3
B_1C_1	219.2	204.0	15.2	7.4
B_2C_2	105.6	119.5	−13.9	−11.6
B_3C_3	−108.1	−120.5	−12.4	−10.3
B_4C_4	−219.4	−207.0	−12.4	6.0
C_1D_1	76.1	67.4	8.7	12.9
C_2D_2	38.2	40.3	−2.1	5.2
C_3D_3	−35.8	−40.7	−4.9	12.0
C_4D_4	−76.6	−70.5	6.1	8.6

Experiments Upon the Distribution of Stresses in a Hexagonal Frame with Continuous Longitudinal Members When Subjected to a Torque

Two experiments were carried out upon the structure with a torque of 12,124 inch lbs. applied as in the case of the pin-jointed structure, *i.e.*, by an upward load of 280lbs. at joint D_3 and a downward load of the same amount at D_6.

Experiment 4

Keel member $\frac{7}{8}$in. solid steel.
Bulkhead D radially braced with 4 B.A. rods.
No bracing in remaining bulkheads.

The measured loads in the wires are given in Table XXVI. In the pin-jointed case the theoretical load in each wire is 72.8lbs. and the variation obtained was from ±70.5lbs. to ±75.5lbs.

In the present experiment the variation is considerably more, although the average wire load in each bay is near the theoretical figure, thus—

In bay AB average load = 72.68lbs.
,, BC ,, = 72.75lbs.
,, CD ,, = 73.31lbs.

The loads in the bulkhead wires were measured in this experiment for comparison with those of the pin-jointed case and are given in Table XXV.

TABLE XXIV.

Member.	Variation of continuous values from pin-joint. Lbs.	Per cent.
A_1B_2	2.4	3.5
A_2B_1	−1.1	4.0
A_2B_3	—	—
A_3B_2	−0.5	−0.5
A_3B_4	6.2	22.5
A_4B_3	—	—
B_1C_2	—	—
B_2C_1	—	—
B_2C_3	−1.1	−1.0
B_3C_2	−2.8	2.7
B_3C_4	—	—
B_4C_3	0.6	0.9
C_1D_2	0.7	1.3
C_2D_1	3.7	8.4
C_2D_3	−2.1	2.0
C_3D_2	—	—
C_3D_4	2.0	4.3
C_4D_3	0.4	0.8
A_1B_1	5.0	1.4
A_2B_2	−10.1	−5.1
A_3B_3	−6.9	−3.6
A_4B_4	14.2	4.0
B_1C_1	6.7	3.2
B_2C_2	−7.1	−6.1
B_3C_3	−4.8	−4.1
B_4C_4	3.7	1.7
C_1D_1	5.6	8.1
C_2D_2	−0.5	−1.3
C_3D_3	−1.9	−4.8
C_4D_4	3.1	4.3

TABLE XXV.

Member.	Load in lbs. Pin-joint case*	Continuous case.
D_0D_1	10.2	7.8
D_0D_2	−81.6	−83.6
D_0D_3	104.5	102.3
D_0D_4	—	9.1
D_0D_5	—	−82.4
D_0D_6	—	102.4

Experiment 5

Keel member $\frac{7}{8}$in. solid steel.
Bulkhead D radially braced with $\frac{5}{8}$in. steel rods.
No bracing in remaining bulkheads.

This experiment was the same as the previous one with the exception that the D bulkhead was more stiffly braced. The results are given in Table XXVI. The pin joint case showed a maximum load variation of ±70.5 to ±74.5. The

* Average of two sides of structure.

maximum variation from the theoretical figure of 72.8lbs. is 17.6 per cent. in the member B_6C_5 and only one other member shows a variation of more than 10 per cent. from the theoretical pin joint case.

The average load in the wires of each bay are

In bay AB average load = 72.47lbs.
,, BC ,, = 73.25lbs.
,, CD ,, = 72.75lbs.

The torsion experiments show a greater variation from the pin-jointed case than do the shearing force experiments, but even these are in most cases sufficiently small to fall within the limits of design accuracy.

TABLE XXVI.

Member.	Loads. Experiment 4.	Experiment 5.	Member.	Loads. Experiment 4.	Experiment 5.
A_1B_2	71.2	70.3	A_4B_5	72.3	69.4
A_2B_1	−71.6	72.7	A_5B_4	−71.8	−71.5
A_2B_3	76.5	74.6	A_5B_6	73.5	73.7
A_3B_2	−75.0	−75.7	A_6B_5	−76.3	−76.0
A_3B_4	72.9	72.6	A_6B_1	70.1	72.0
A_4B_3	−70.7	−71.1	A_1B_6	−70.3	−70.0
B_1C_2	71.7	70.1	B_4C_5	68.3	67.8
B_2C_1	−66.6	−73.4	B_5C_4	−69.0	−71.9
B_2C_3	83.1	83.0	B_5C_6	75.6	75.3
B_3C_2	−75.0	−74.4	B_6C_5	−84.0	−85.6
B_3C_4	71.3	67.8	B_6C_1	67.5	69.8
B_4C_3	−69.2	−70.9	B_1C_6	−71.7	−69.0
C_1D_2	70.3	69.3	C_4D_5	72.2	69.8
C_2D_1	−66.7	−69.7	C_5D_4	−66.9	−69.3
C_2D_3	82.8	77.2	C_5D_6	82.4	78.0
C_3D_2	−75.4	−72.8	C_6D_5	−75.9	−73.0
C_3D_4	71.7	72.3	C_6D_1	72.5	70.9
C_4D_3	−71.7	−76.3	C_1D_6	−71.3	−74.4

AEROFOILS

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I.

On measuring the camber of a pigeon's wing it was found that there was a gradual increase from the tip to the elbow, the curve of maximum thickness of the wing section plotted against distance from the elbow was found to be approximately hyperbolic, thus the bird possesses a range of aerofoils suited to any requirements of flight.

As the wing in its downward beat also moves forward the tip will obviously travel at a greater speed in the direction of flight than a point on the wing nearer the root. So that for aerodynamical, as well as for structural, reasons the camber is small towards the tip, as is suitable for high-speed aerofoils.

At a point beyond the wrist of the wing, at about half the wing length, the camber is in the region of 0.05, the value which gives the maximum L/D for aerofoils. The camber near the elbow is comparatively high, ranging from 0.18 to 0.195 for the wings measured. These values are greater than those usually adopted in aeroplane practice.

Whether these big cambers obtain in actual flight, or whether they can be altered by adjustment of the contour feathers by the bird at will. are matters of conjecture, but a camber of this amount gives a value of L/D of only 67 per cent. when compared with a camber of .05.

Perhaps the comparison of such an aerofoil with the rigid one we are using as a standard is not valid.

Apart from the high value of the camber found in a natural aerofoil the most striking fact is the position of the maximum ordinate.

In no case was this found to be at a greater distance from the leading edge than 0.21 of the chord.

Comparing this with the value of .33, which has been found to be the best position with experimental aerofoils, the difference is surprising.

Further, the position of the maximum ordinate advances towards the leading edge of the wing as the distance from the root increases, as will be seen by comparing section D and C in the diagrams (Figs. 1 and 1*a*).

It is worthy of passing notice that each feather has its own individual camber and also that there is a reversal of curvature at the trailing edge of the rowing feathers, which seems to indicate that this design is suitable for high speeds, as experiment has proved to be true in the case of aerofoils in general.

It would appear that the part of the wing devoted mainly to sustaining the weight is of large camber while the propelling part of the wing is of small camber.

II.

There is an interesting method of considering the air flow over the upper front surface of an aerofoil which, although in no way exact, does give an indication of what happens.

It further leads to an explanation, which may be accidental, of the most effective flying angle of an aerofoil. Consider two sections, A and B, on the

upper surface of an aerofoil at a distance l apart (Fig. 2) on which a fluid impinges at an angle α with the horizontal.

At some distance from the aerofoil there will be a stream line CD which is unaffected by the presence of the aerofoil.

Then ACDB may be considered to be a channel down which the fluid is flowing from B to A in a direction parallel to CD.

If the fluid were incompressible the diminution of pressure from B to A could be found by the application of Bernouilli's theorem, the ratio of the areas at B and A depending upon the inclination of the relative air stream and the length l.

This explains the development of a suction on the upper surface of an aerofoil.

The resistance in such a case would, for similar velocities, be proportional to l.

Consequently, neglecting all other parts of the aerofoil, the direction of the air stream which gave the maximum difference of area between the points B and A for the minimum distance of these sections apart would give the greatest value of L/D, since the lift would be proportional to the difference of pressure between B and A, and the drag would be proportional to l.

From a consideration of various aerofoils the prediction given above is actually true.

Taking the case of the aerofoil illustrated in Fig. 3, if we draw the air stream at various inclinations tangential to the curve of the upper surface of the aerofoil and from O drop a perpendicular on to this tangent we obtain BB′, AA′, CC′, etc., which are proportional to the drag, and OB, OA, OC, etc., which are proportional to the lift.

In Fig. 3 BB′ is horizontal, AA′ at 4°, at which angle the value of L/D is a maximum and CC′ is at 16°.

As will be seen the ratio OA/AA' has the greatest value.

The same result was found for the other aerofoils, Figs. 4 and 5.

In Fig. 5 the points B″, C″ and D″ are given through which the profile of the aerofoil should pass to give a constant value of the L/D ratio here given for the range from 0° to 48°. This curve would differ only slightly from the actual form used.

III.

Consider next an aerofoil with a rotating leading edge. If the rotating cylinder forming the leading edge be imagined to carry with it a film of air, then continuing with the same line of reasoning we obtain a simple explanation of the " magnus effect."

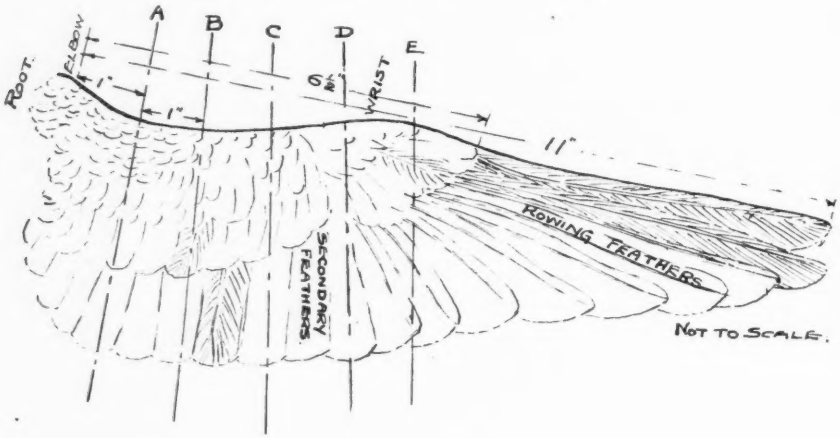
With the cylinder (Fig. 6) rotating in a direction such that the upper surface is moving in the same direction as the air stream, then, if it carry with it a film of air represented by EFG, the effective channel of flow of the impinging air will now be ECDF, on the same simple basis of reasoning.

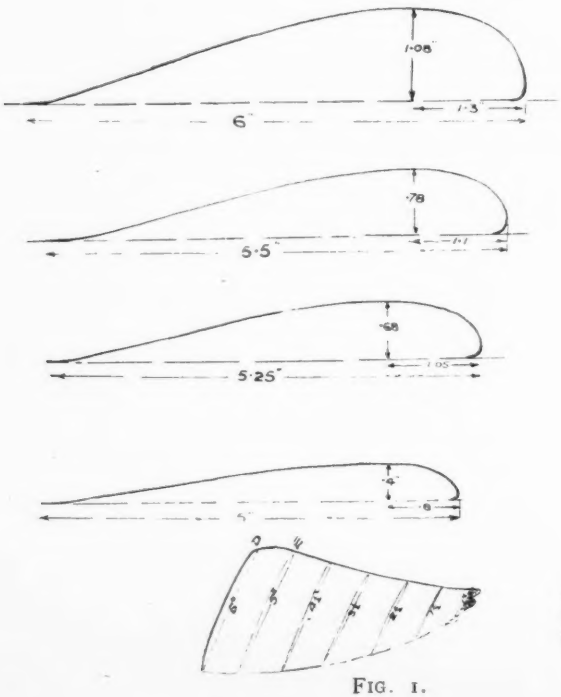
That is, the ratio of areas will be FD/EC, whereas with a non-rotating leading edge the ratio of areas would be BD/AC. But the ratio FD/EC is greater than the ratio BD/AC from the geometry of the figure, consequently the fall in pressure from D to C will be greater, *i.e.*, the lift will be increased.

Further, considering the under surface of the aerofoil, the forward momentum of part of the impinging air stream will be partially destroyed by the rotating

air film with a consequent increase of pressure on the under surface which will have the effect of further increasing the lift of the aerofoil.

Varying Camber of a Pigeon's Wing (*No.* 1).





Section A.
Scale Full Size.
Camber = 1.08/6 = .18
at 0.207 of chord from leading edge.

Section B.
Scale Full Size.
Camber = .78/5.5 = .142
at 0.20.

Section C.
Scale Full Size.
Camber = .68/5.25 = .13
at 0.2.

Section D.
Scale Full Size.
Camber = .4/5 = .08
at 0.16.

After Section D the wing tapers down uniformly to the thickness of a feather.

FIG. 1.

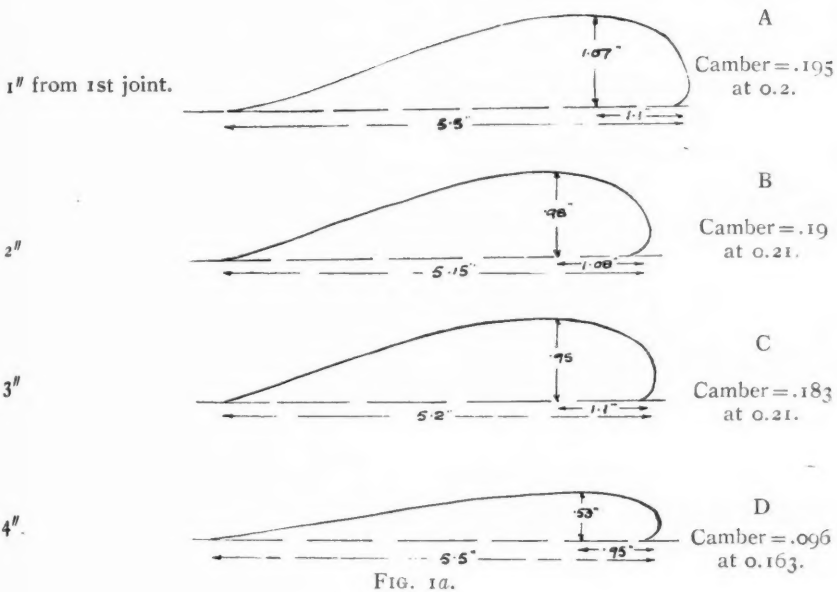


FIG. 1*a*.

Left Wing of Pigeon (*No.* 2).

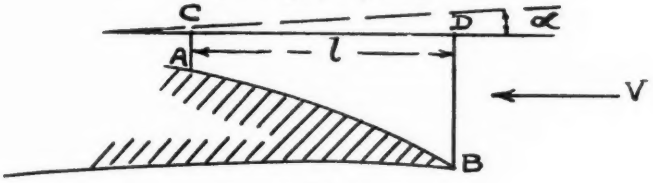


FIG. 2.

FIG. 3.

Aerofoil No. 64.

$OB/BB' = 2/6.6 = .304$

$OA/AA' = 1.6/4.25 = .337$

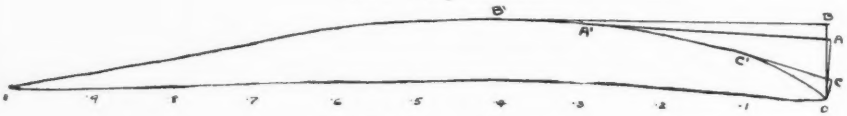
$OC/CC' = .8/2.7 = .297$

BB' inclined at 0° to horizontal

AA' ,, 4° ,,

CC' ,, 16° ,,

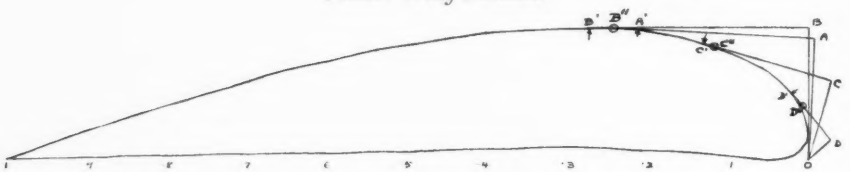
FIG. 4.
Avro Wing Section.



$OB/BB' = 2.35/10.2 = .23$
$OA/AA' = 1.85/9.7 = .238$
$OC/CC' = .66/3.1 = .213$

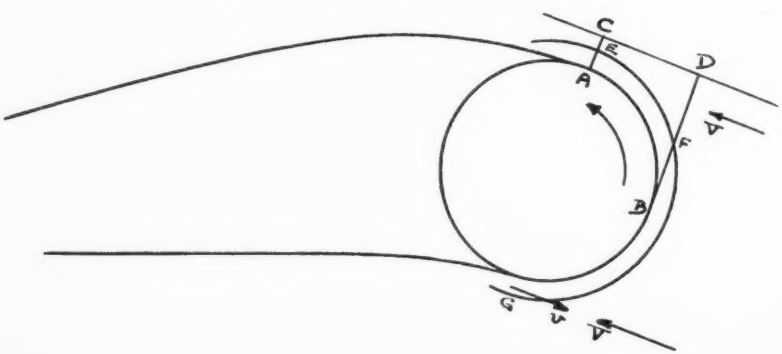
BB'	inclined at	0°	to horizontal
AA'	,,	3°	,,
CC'	,,	16°	,,

FIG. 5.
Fokker Wing Section.



$OB/BB' = 4.1/7 = .585$
$OA/AA' = 3.8/5.55 = .67$
$OC/CC' = 2.56/4.2 = .61$
$OD/DD' = .95/1.9 = .5$

BB'	inclined at	0°	to horizontal
AA'	,,	2°	,,
CC'	,,	16°	,,
DD'	,,	48°	,,



SOME REMARKS ON THE "PROOF STRESS"

BY ERNEST SKERRY

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Although aircraft construction and design, when steel is used, is based on the elastic limit, it has been found, in the case of steel strip, to be so indefinite a point that its correct determination is difficult, if not impossible.

It has been necessary, therefore, to fix a definite point as near the elastic limit as practicable, but capable of being read more easily and accurately.

The "proof stress" was evolved to meet these requirements, and its definition is given by the British Engineering Standards Association as "the greatest load per square inch, which, when applied for 15 seconds and removed, produces a permanent extension of not more than .1 per cent. of the gauge length."

The proof stress, then, may be said to be the elastic limit plus a constant.

It is necessary, in order to arrive at the proof stress, to fix theoretically the elastic limit, and in order to explain this, reference must be made to the Air Board specifications dealing with steel strip, and S.40 Specification may be taken as being fairly representative.

This specifies a proof stress of 65 to 75 tons per square inch, and gives an extension limit for each load as follows:—

"At 65 tons per square inch, the extension (on a 4in. gauge length) must be not more than .025."

"At 75 tons per square inch, the extension (on a 4in. gauge length) must be not less than .028."

When the extensions are between these limits it follows that the proof stress is somewhere between 65 and 75.

Whilst this arrangement is satisfactory for the purpose of fulfilling the specification, it does not help very much when it is required to determine the exact proof stress.

This may be accomplished, however, by taking extension readings at frequent points, from which a stress-strain diagram may be plotted, and by also plotting the theoretical line of proportionality, or "elastic line," the proof stress may be read as that point where the curve leaves the line of proportionality by a distance equal to .1 per cent. of the gauge length. This is illustrated in curve "A."

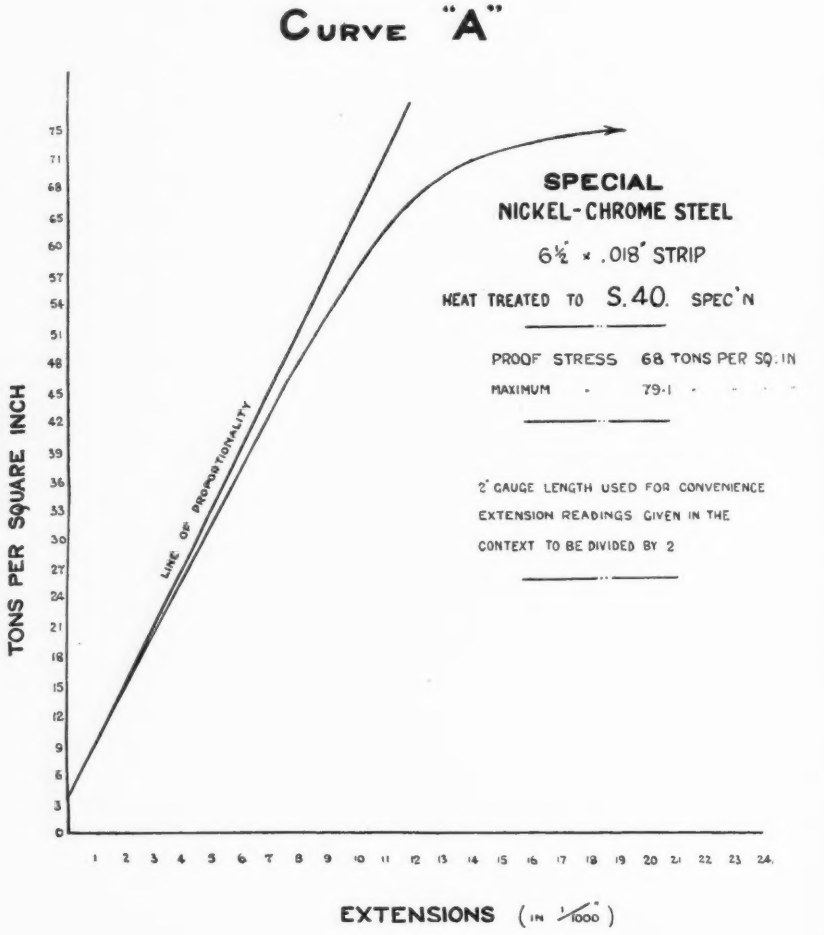
To return to the theoretical elastic limit, this is fixed by the extension limits mentioned above, which are calculated on the formula $x = fl/E$.

x = extension.
f = load (tons sq. in.).
l = gauge length.
E = Young's Modulus of Elasticity (12,500 tons sq. in.).

Then in the case of S.40 Specification, the extension at 65 is $(4 \times 65)/12500 = .0208$, and the constant being added $.0208 + .004 = .025$in.

A study of any of the curves shown will reveal the fact that in all probability the elastic limit occurs at a much lower tonnage than is generally thought, as contrary to the practice of other classes of steel, the curve appears to leave the line of proportionality, slightly, almost all the time, increasing of course more rapidly and to a greater extent at the supposed true elastic limit.

It may be that the steel is not, as has been thought, truly elastic, even within the limit of proportionality, and if this is true, the modulus may not be altogether applicable to this class of material. Even so, it would appear that the allowance of .1 per cent. of the gauge length is quite sufficient to cover any discrepancy which takes place in the early stages of the test.



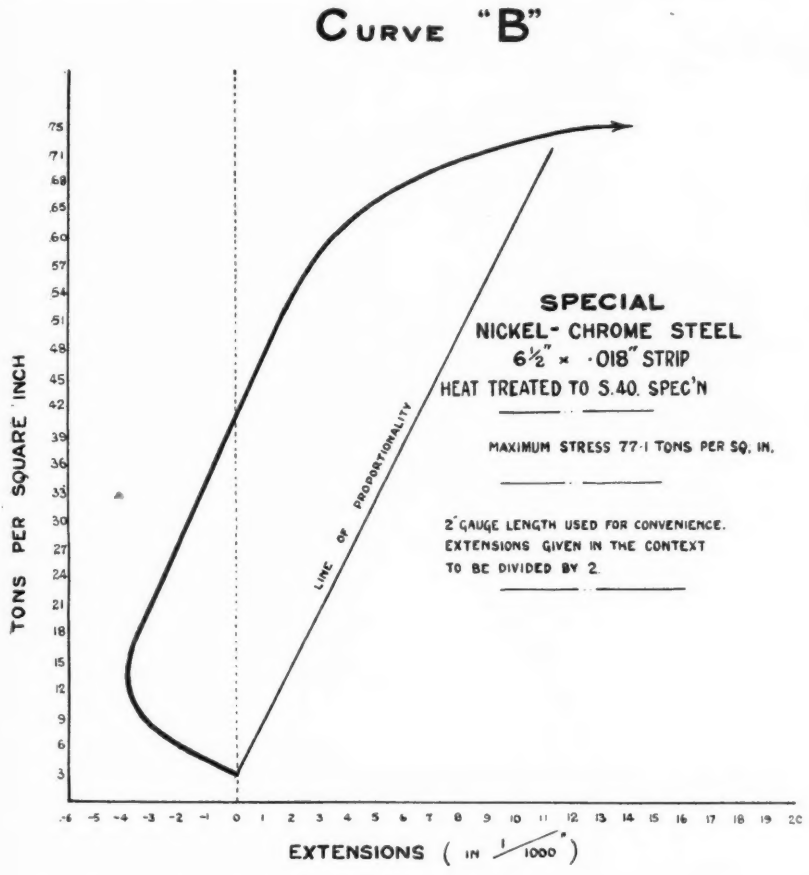
Then the question arises as to what period, or length of period, the constant may be added, and it may be answered that it should be added to the total extension from zero to the load representing the proof stress.

That this would give rise to further errors I will try to demonstrate.

Should a test piece be taken from a length which has been heat-treated in the coil instead of in a straight length, it is naturally slightly bowed, having taken its shape from the coil, and owing to its tensile strength remains so, unless it is kept in tension.

It is obvious, therefore, that any extension readings taken before this bow is removed are not true extensions, but are merely due to the piece straightening.

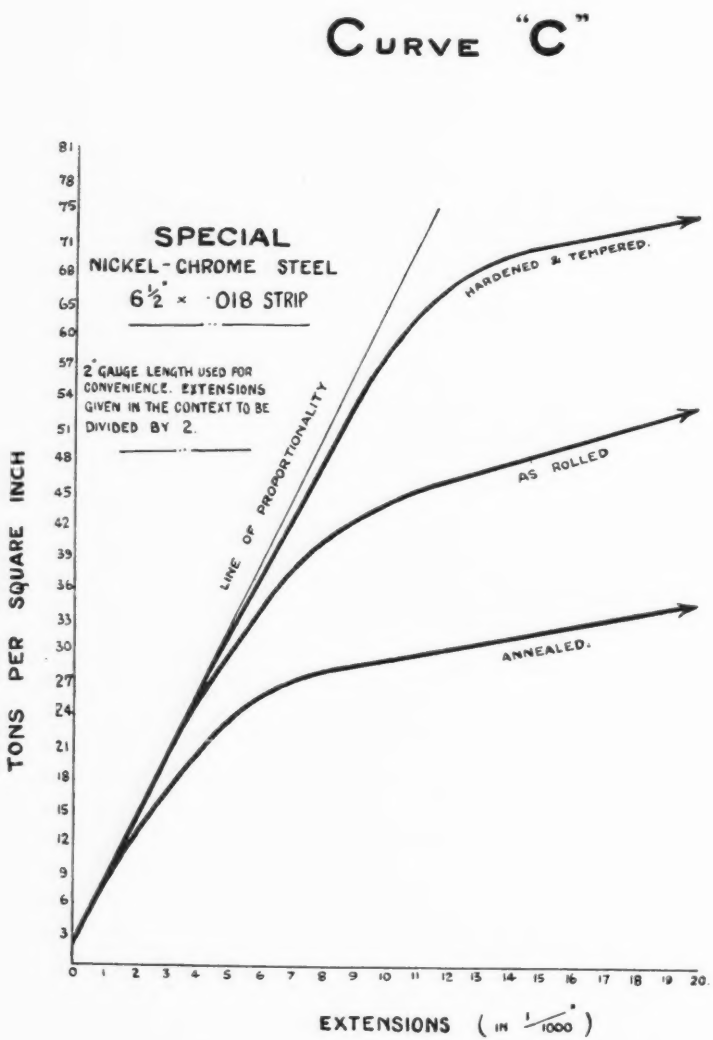
In the same way false readings may be obtained owing to the presence of small buckles which sometimes occur in strip steel pieces.



It will be noticed that in curve "B" negative readings were obtained due to the fact that the bow was placed concave side to the spring dial gauge (which was used for measuring the extensions), which had the effect of closing the gauge when the piece began to straighten. In this latter case it would be difficult to determine when to commence reading true extensions, or what allowance to make in order to compensate the negative readings.

The proof stress, of course, is in direct ratio to the maximum stress, so that with a low maximum stress a low proof stress may be expected and *vice versa*. It has often been found, however, that the total extension taken from zero to the proof stress load does not always bear out this fact, the extension sometimes suggesting a low tensile when the maximum stress is high, whereas extensions taken, say, from 55 to 65, and 65 to 75 tons per square inch, are quite in accordance with the remainder of the test.

In the same way it has been noticed in a number of tests, giving a low maximum stress, that the extensions are very small, pointing to a very high tensile stress, and more often than not these results have been due to the fact that negative readings were obtained at the beginning of the test, before the piece had straightened out.


CURVE "C"
SPECIAL
NICKEL-CHROME STEEL
6½" × ·018 STRIP
2" GAUGE LENGTH USED FOR CONVENIENCE. EXTENSIONS GIVEN IN THE CONTEXT TO BE DIVIDED BY 2.
LINE OF PROPORTIONALITY
HARDENED & TEMPERED.
AS ROLLED
ANNEALED.
TONS PER SQUARE INCH
81 78 75 72 68 65 60 57 54 51 48 45 42 39 36 33 30 27 24 21 18 15 12 9 6 3
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
EXTENSIONS (IN 1/1000")

In view, then, of these facts, it would seem very advisable to take the readings at a high load instead of from zero. Of course, they could be taken between 50 and 65, or even 45 and 65, but lower than that is not advisable, and the last 10 tons seems to be the best range on which to work.

The extension limits for 55 to 65 and 65 to 75 are as follows:—

$x = fl/E + .1$ per cent. gauge length, then $(10 \times 4)/12500 + .004 = .0072$.

With regard to adding the constant to the range of extension from 55 to 65, it has been my experience that the constant may be added at any stage or for any range of extensions without influencing the result in the slightest, one way or the other, providing, of course, that it is added within the limit of proportionality.

In conclusion, a curve showing the influence of heat treatment on the ratio of the proof stress to the maximum stress may be of interest. This is illustrated in curve "C."

A coil was taken from a standard cast and tested in three conditions:—

1. As rolled, ready for hardening and tempering.
2. Annealed at 800° Cent., and allowed to cool slowly with the furnace.
3. Hardened at 820° Cent., quenched in water, then tempered at 470° Cent., and quenched in water.

Results were obtained as follows:—

1.	*Proof Stress*	43	tons	sq.	in.	*Max. Stress*	56	tons	sq.	in.	*Ratio*	76.7
2.	,, ,,	26	,,	,,		,, ,,	53	,,	,,		,,	49.0
3.	,, ,,	69	,,	,,		,, ,,	81	,,	,,		,,	85.1

REVIEW

The Adventure of Wrangel Island

By Doctor Vilhjalmur Stefansson. (Jonathan Cape, Ltd., 18/-.)

The impression left on the reader when turning off the light in the early hours of the morning, is that "Stef" did well to name his account of the expedition to Wrangel Island the "Adventure" rather than the "Tragedy," for it is the spirit of adventure which survives in the diary so faithfully kept by Lorne Knight from September, 1921, to March, 1923.

Crawford, Knight, Maurer, Galle and Ada Blackjack sailed from Nome, Alaska, to Wrangel Island—seven hundred miles north-west beyond the Arctic Circle—to hold that hitherto unclaimed land for the freedom of air travel, until England or America should confirm that freedom. Until the prospect of air travel across the Arctic had been foreseen by Dr. Stefansson as the nearest route between the civilisation of East and West, when journeys of three thousand miles by air would bring the East within a week-end journey of the West, Wrangel Island had little significance. Now it is recognised that its strategical value as a stepping stone makes that very isolation its main attraction. In the late summer in some years the Island is freely accessible, as Crawford and his companions found when they landed from the schooner "Silver Wave" in September, 1921, after sailing from Nome without one glimpse of ice to bar their way. In other years, as in 1922, the schooner sent to their relief was barred by floating ice from approaching the Island, and the relief was delayed until the following summer. It was in that second year that the adventure developed into a tragedy, for when the schooner "Donaldson" arrived in August, 1923, she found that Ada Blackjack was the sole survivor of the expedition. How the four men had spent their time through the first year and second winter is faithfully recorded by Knight in the Diary which he kept up to his death in 1923, the diary of a man written in similar circumstances to those

of Scott's diary, written to the end with the knowledge that he would never see it published and recording the developments of scurvy, which must prove of great value in the treatment of that disease. And after Knight had died and left Ada alone on the Island, how for the months which followed before the arrival of the "Donaldson," she and the cat lived by hunting, is a story which illustrates the resource of a woman when faced with the problem of relying for existence entirely on her own efforts. The story of the whole adventure is written with Dr. Stefansson's inimitable lucidity, and must remain a classic in the history of Arctic Exploration.

Many members of the Royal Aeronautical Society have met Dr. Stefansson on one of his several visits to London. In May, 1923, he was sent over here by the Canadian Government to present the case of the Nationality of Wrangel Island to the British Government, and on that occasion he came to know that courageous member of the Cabinet, Colonel the Right Hon. L. S. Amery, then Minister of the Colonies. In the present book Colonel Amery has contributed a Foreword, in which he says that more than any other living man Dr. Stefansson has "been responsible for a change in our outlook upon the Arctic, a change destined to open a new epoch in world communications, and to exercise all the profound effect upon economics and politics that every such change has exercised in the past. Others may have made more sensational expeditions, though his own record of exploration is in itself a very remarkable one. But he has been in a peculiar sense the philosopher and the prophet of the coming era. Convinced by his own experience over many years of the falsity of certain current ideas about the Arctic, he has set himself to overthrow them and to replace them by that wholly new conception which he has set forth so interestingly both from the practical and from the historical point of view in "The Friendly Arctic" and in "The Northward Course of Empire."

Colonel Amery further points out that "the Arctic Ocean is the smallest of the oceans, a mere Mediterranean, in fact. It would indeed be peculiarly entitled to that designation, for it is practically at the centre of the land hemisphere. Once an easy means of traversing it is devised its wonderful central situation is bound to make it one of the world's great highways. Aviation clearly indicates the means, and Amundsen's successful flight to within a few miles of the Pole, shows that the practical opening up by airship of the great Northern routes across the world is not very far distant."

Colonel Amery concludes his illuminating Foreword with a message to British youth that "the conception which inspired the undertaking described in this volume and the spirit of the brave youths who carried it out matter very much indeed to us as a nation and an Empire, and give permanent interest to the simple narrative of an unsuccessful adventure."

Amongst the names of those who supported the rescue expedition of 1923, are those of the Duke of Sutherland, Lord Milner, Lord Lee, Lord Egerton, Mr. Orville Wright, Lieut.-Colonel McClean, Sir Mortimer Singer, Mr. H. O. Short, and others well-known in aeronautical circles.

For those readers who wish to go still more deeply into the details of the Wrangel Island adventure than can be learnt by the perusal of Dr. Stefansson's narrative, a photostat copy of Knight's Diary has been made and is now in the library of the Royal Aeronautical Society, where it is open to inspection. This is the only facsimile copy of the diary in England, but a typewritten copy is being made for general reference and for presentation to the Royal Geographical Society, of which Dr. Stefansson is a Gold Medallist.

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